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Comparative market analysis and economic simulation for Morocco of the parabolic trough and dish CSP technologies

Veronika Lemmer

Dissertação de Mestrado Integrado em Engenharia da Energia e do Ambiente

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Trabalho realizado sob a supervisão de

João Serra

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Abstract

Developments in the past years have differentiated CSP (concentrating solar power) technologies (parabolic trough, power tower, parabolic dish and linear Fresnel) in terms of matureness. The aim of this Thesis is to compare the parabolic trough technology with the parabolic dish and to evaluate the economic feasibility of a project in Morocco. A general survey of the technology is presented and a market analysis is carried out. Finally the currently running power plants and planned projects are brought together in a database and presented. After comparing the two technologies, it was clear that parabolic trough is in a much more mature state than the parabolic dish, in terms of market penetration.

In fact, project analysis for the parabolic dish would not make sense as there are no commercial products for large scale and many assumptions would need to be made. Therefore a project analysis was developed only for the parabolic trough technology. For the location, the largest cities in Morocco were chosen, an ambient and solar database was created and the annual electricity generation was calculated using the program SAM. Indicators such as the LCOE, IRR and NPV were calculated for two different power plant designs, one adapted for 5% of CSP integration in the grid and one for 20% of CSP integration. Locations with higher solar resource and 20% of CSP integration have the best results. For the IRR 10.2% is estimated for Tangier and 9.9% for the area of Salé Rabat and Kenitra. Estimated net present values are 3.7 M€ for Tangier and 0.7 M€ for Sale, Rabat and Kenitra.

Keywords: CSP, LCOE, market, Morocco.

Resumo

Nos últimos anos tem-se notado um rápido desenvolvimento, ainda que diferenciado das tecnologias de concentração solar CSP (concentradores parabólicos lineares e de Fresnel, discos parabólicos e torres de concentração solar). O objetivo desta Tese consiste em comparar a tecnologia parabólica linear com o disco parabólico e em analisar a viabilidade económica para um projeto em Marrocos. É apresentada uma análise geral da tecnologia e uma análise de mercado. Por fim é construída uma base de dados contendo as centrais atualmente existentes e planeadas em projetos para o futuro. A comparação dos dois mercados leva a concluir que os sistemas parabólicos lineares se encontram num estado muito mais avançado do que os sistemas baseados em discos parabólicos.

Desenvolver uma análise de projeto para o disco parabólico não faria sentido, visto que não existem produtos comerciais para aplicações em larga escala, o que levaria à necessidade de fazer várias suposições para vários parâmetros-chave. Foi então desenvolvido uma análise de projeto para o sistema parabólico linear. Foram escolhidas as cidades com maior número de habitantes em Marrocos, para as quais se construiu uma base de dados de condições ambientais e recurso solar para, por fim, calcular a produção de eletricidade utilizando o programa SAM. Para dois dimensionamentos diferentes da central, adaptados a uma integração de CSP na rede elétrica de 5% e 20% respetivamente, foram calculados indicadores tais como o LCOE, a TIR e o VAL. Os melhores resultados foram obtidos para locais com maior recurso solar e com o dimensionamento adaptado a uma integração de 20% de CSP. A TIR foi estimada com 10.2% para Tânger e 9.9% para a zona de Salé, Rabat e Kenitra.

Palavras-chave: CSP, LCOE, mercado, Marrocos.

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1. Introduction

The global electricity demand is expected to increase rapidly, at a rate of 2.2% [5]. For the electricity grids, which have to adapt instantaneously to the demand, are forced to increase their installed capacity of electricity generation. When choosing which type of electricity generation is to be increased, the country chooses at the same time which positive and negative impacts of the selected technology and energy source will be affecting the future the country. These impacts are related to the total cost, to the dependence on finite energy sources from other countries or non-independence by using renewable sources, the environmental impacts and risk which are brought during the whole lifespan of a power plant. For now total worldwide installed capacity is in the range of 5 TW, and it shows that non renewable energy sources have been the first option, representing 78.3% of the total capacity [1H]. About 16.5% is related with hydro generation, and only 5.2% to other renewable sources. But on the other hand, developments in the last years shows that renewable sources are increasingly important. The average annual growth rates of renewable energy capacity for the period 2007-2012 was 60% for solar PV, 43% for concentrating solar thermal power, 25% for wind power, 3.3% for hydro-power and 4% for geothermal power [1H].

Dominant renewable electricity technologies are wind turbines, solar PV and bio-power, which had 283 GW, 100 GW and 83 GW of worldwide installed capacity by the end of 2012. Beside these, there are still new technologies emerging. One category are solar concentrating power (CSP) technologies. For these, there are four main subcategories, two linear concentrators, the parabolic trough and linear Fresnel, and two point focusing concentrators, the power tower and the parabolic dish. Parabolic trough power plants use one axis tracking parabolic shaped reflective surfaces which concentrate the sunlight onto a receiver tube, in which a heat transfer fluid runs. This heat transfer fluid is used to transport the heat from the solar field to the power block, where a thermodynamic cycle converts the heat into electricity. Fresnel systems are similar, with the main difference being the reflective surface, which are several long flat mirrors. Power tower consists on several dual axis tracking flat mirrors - heliostats- which are positioned around a tower. The heliostats reflect the sunlight to the top of the tower, where a receiver is positioned. All these three technologies are well adapted to include thermal storage systems. The fourth technology, the parabolic dishes, are dual axis tracking single parabolic shaped dishes which concentrate the sunlight to the center. At the center a receiver absorbs the sunlight and provides high temperature heat to an energy conversion subsystem, like the Stirling engine.

The scope of this thesis is to deeper analyze how the parabolic trough and parabolic dish have developed the last years, how mature the technology is and how developed their markets are. There are three main chapters, the first two focus on each of these technologies, and in the third the results of an economic simulation for Morocco with the parabolic trough technology is presented. For each technology a analysis of the technical aspects is shortly described. Than a market analysis is carried out, and the main companies and benchmark products are listed. Finally the existing and planned projects are reviewed for all over the world. In the third section, where the simulations are presented, first the moroccan electricity system is described. Than the methodology used for the simulations is presented, describing how was proceeded to define the reference power plant technical and dimensional details. Than it is described which assumptions were made in terms of which data were used and which equations were used. Finally the results are presented as well as a sensitivity analysis for the most uncertain variables, such as the investment, electricity tariff and residual value.

Parabolic dish

1.1 General analysis of the technology

As many other electric thermal solar generation technologies and even many traditional power generation technologies, the solar dish produces heat which is converted into electricity. It consists on a parabolic dish that concentrates solar radiation onto a receiver, where high temperatures are achieved. A dual-axis tracking system is used to track the sun along the day. The high temperatures create a heat flux that is transferred to the energy conversion subsystem. Different engines such as Stirling engines, gas turbines, thermoelectric generators and steam engines can be used. But in the past, most attention has been given to the Stirling engine [8A] that can convert up to 32% of the incoming solar energy to electricity [9A]. It produces mechanical power through a thermodynamic cycle and finally electricity, through a coupling with an electric generator. More details about the Stirling engine and thermoelectric generator will be described in the next sections.

The solar dish has the great advantage of modularity, so that the power plant dimensions can be adjusted to the needs. Additionally the production can start gradually before the entire power plant is finished, creating early positive earnings. It can be a small generation unit, like for agriculture pump sets, and operate in remote locations. Or it can be large industrial scale for electricity production with low environmental impacts. In this case, peak production hours are coincident with peak demand hours as with PV, which is an advantage comparing to other energy sources like wind power. Comparing to line focusing systems, it has the advantage that a failure of one unit will have a small impact on the whole production, as the other units continue to work. Less land preparation is needed comparing to any other solar thermal power plants. The solar dish is adapted to areas with slope. Unfortunately due to the tracking system, there is an additional cost including a more rigid frame and maintenance for moving parts.

1.1.1 Tracking system, concentrator

The concentrator follows the sun with a two axis tracker. It can be a azimuth-elevation tracker (Figure 1a) or a polar tracker (Figure 1b). Typical for large dishes are azimuth elevation tracking systems (dish rotates in a plane parallel to the earth (azimuth) and in a plane perpendicular to it (elevation)). Typical for small solar dishes are polar tracking systems (dish rotates constantly with 15º/h around an axis parallel to the earth's axis of rotation and rotates slowly with the declination axis (perpendicular to the polar axis, the angle varies by +/ 23.5o over a year)).

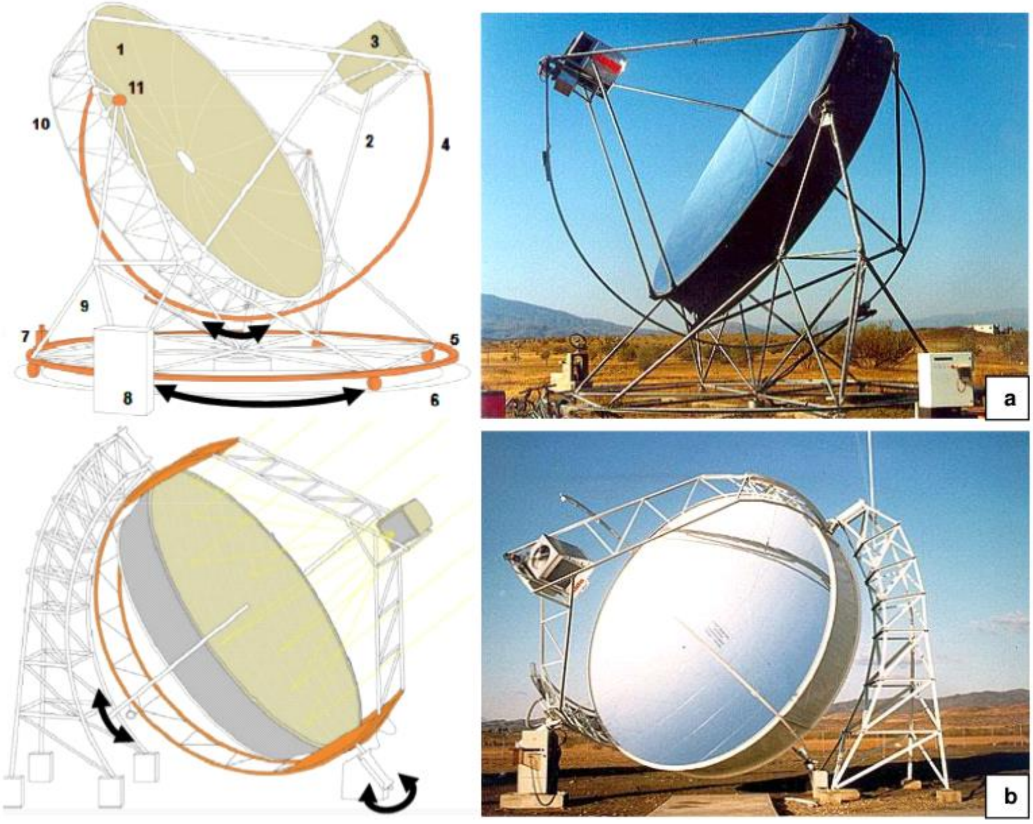


Figure 1 - Tracking systems - azimuth elevation (a) and polar axis tracking (b). Ref. [15B]

There are three main types of concentrators. One type is the glass-faceted concentrator, which uses aligned curved glass mirrors. But it has not been widely used because it is expensive and heavy. Another type is the entire paraboloid dish, but they showed low optical efficiency. The material of the reflective surface usually is metalized glass or plastic. The most durable ones are silver glass mirrors (reflectance of 90 – 94%). The third type of concentrators are thin metal or plastic membranes with a reflective coating. They are fixed on a metal ring, and the pressure difference between front and back is used to fix the paraboloidal form. They use low cost polymer films for which flexibility is required, therefore thicknesses is usually of ~ 1 mm. Low iron content improves reflectance. [15B].

The size of the concentrator depends on the power. Typical concentrator diameters are 5 m – 10 m. For several 25 kW dishes that were build in the last years, the diameter is 8,5 m. The ideal form would be a parabolic shape.

Good indicators of concentrators quality are the concentration ratio and intercept fraction. The concentration ratio is the solar flux through the receiver aperture divided by ambient direct normal solar irradiation. Typical values are higher than 2000. The intercept fraction is the fraction of the reflected solar flux that passes through the receiver. Typical values are around 95%.

1.1.2 Receiver

To transform the radiation into heat, a receiver is placed in the focus region of the concentrator. To avoid too high fluxes per area, the absorbing surface is located behind the focus. Usually there is an aperture at the focus to reduce radiative and convective losses.

Stirling receivers efficiency is usually ~90%. They can be direct illumination receivers or indirect receivers. For direct illumination receivers, small heater tubes with high velocity and pressure helium or hydrogen absorb the concentrated solar flux. They are placed directly in the concentrated solar flux region. Liquid-metal, heat pipe solar receivers (indirect receivers) are used when uniform temperatures are essential (as for multiple piston Stirling engines). The liquid sodium metal condensates on the Stirling engine's heater tubes and vaporizes on the absorber surface. The receiver temperature can achieve 1080K.

There are significant radiation and convection losses in the receiver. Comparing to these, using a proper insulation (high-temperature ceramic fiber), conduction losses should represent less than 2% of the total receiver losses [2A]. Convective losses depend on the receiver temperature and geometry, aperture orientation, diameter and wind speed. Radiative losses increase with the temperature of the receiver (emission) and reflectance of the cavity surfaces.

1.1.3 Energy conversion subsystem

1.1.3.1 Stirling engine

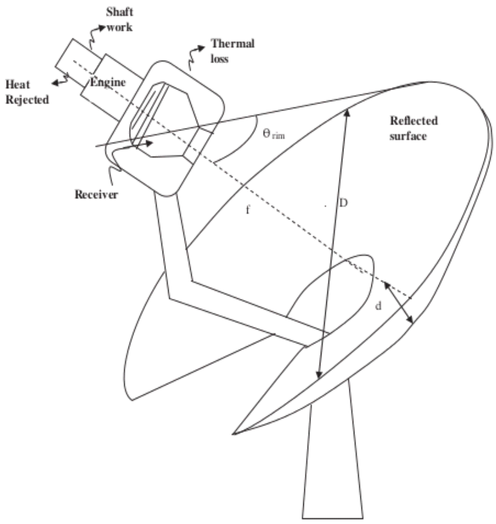


Figure 2 - Schematic diagram of a solar parabolic dish using Stirling engine[2].

The Stirling engine converts heat into mechanical work. Applying this engine to a solar parabolic dish, the heat available at the focus point is used to produce mechanical work (Figure 2). The mechanical work can be easily converted to electricity through a conventional generator or linear generator. As the internal combustion engine or a gas turbine, the Stirling engine follows a thermodynamic cycle, where a working gas (hydrogen, which is more efficient, or helium, which is more common) passes through expansions, compressions, cools down or heats up [1A]. But the main difference is that in the Stirling engine the cycle is closed, and the processes occur sequentially in different spaces with overlapping borders.

There are two sides in the engine, a cold one and a hot one. The hot side is heated up by the heat source (solar energy), and the cold side is cooled down by a fan or water. Through a working piston, the working gas is moved from one side to the other, passing through an intermediate heat exchanger (regenerator), to optimize the efficiency. The gas absorbs heat isothermally at the hot side and cools down isothermally at the cold side. As a result at the hot side the gas expands, moving the working piston. On the cold side the gas is compressed by the working piston. The energy needed for the compression is always lower than the energy provided by the expansion. The difference between these two energies is the one which will be extracted.

There are two main types of Stirling engines, kinematic and free-piston engines. Kinematic engines such as four-piston engine were developed; they are mechanically connected to a rotating shaft. Free-piston engines have no mechanical connection to the outside; instead of the rotating shaft a spring is used.

Reddy, V. [2A] estimates that for a large scale power plant, more than 2/3 of the power loss takes place at the Stirling engine, followed by the collector. For the same study, the overall energetic efficiency of the system was found to be 29.67%.

The efficiency of the Stirling engine is always lower than the idealized Stirling cycle. This is mainly due to the incomplete heat transfer in the regenerators. This heat transfer depends on the heat exchanger characteristics, the cylinder dimensions and piston speed. Also pressure losses can be important mainly at part-load operation.

1.1.3.1.1 Advantages

One great advantage of the Stirling engine is the high efficiency, nearly 30% of the direct-normal incident solar radiation is converted into electricity (31.25% by Stirling Energy Systems in 2008). This value depends on the temperature range, but even so a solar-powered Stirling engine can operate at low, medium and high temperatures. The whole system has a quick installation and high lifetime, especially for free-piston technology. The overall emissions are low, there are only small amounts of engine oil, coolant or gearbox grease. Finally, the noise level is relatively low, and the main source of noise is the cooling fan, in the case where it is used as the cooling system.

Comparing to a parabolic trough concentrated solar thermal power plant, the annual efficiency is higher [2A]. But the year-round power output is lower because of the heat storage used in parabolic trough power plants.

1.1.3.1.2 Disadvantages

It is easy to produce maximum power, but difficult to maintain a sufficient mean production (it produces 100% at the design radiation otherwise large efficiency drops occurs for lower radiation). Therefore fluctuations will happen in the production, and for an autonomous system much more peak power has to be installed. Storage is not possible for high temperature engines, only for low temperature engines. Otherwise a hybrid system with biomass can be useful, which on the other side is difficult to integrate due to geometrical constrains.

1.1.3.2 Challenges and alternatives for large scale

Stirling technology has faced real challenges. New ideas like using a Brayton cycle motor, producing superheated steam or using a volumetric receiver (HelioFocus, see subsection about existing companies) show other options for the solar dish. An experiment using Brayton cycle motor was done by Brayton Energy. Actually the proven technical advances for this well-known cycle is an advantage. But according to them, for larger systems the Brayton engine is more cost effective when comparing to the Stirling engine, but still the difference is not significant enough [10A]. For HelioFocus, the greatest advantage is that this technology includes storage, through a heat exchange system. Air is heated up to 1000ºC for use in a gas turbine or 650ºC for supporting existing power stations or standalone steam turbines

1.1.3.3 Thermoelectric generators

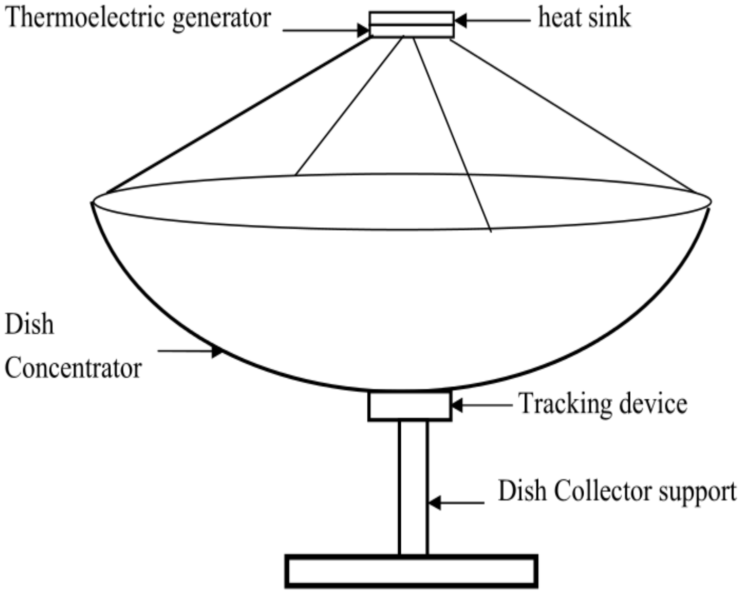


Figure 3 - Schematic diagram of solar parabolic dish thermoelectric generator [6].

Instead of first converting the heat generated at the focus point to mechanical work, thermoelectric generators convert heat directly into electricity (Figure 3). Considering the specific cost, specific weight and power density, it can be seen as competitive comparing to other options [7A]. The temperature difference across the generator is converted into electricity directly by the Seebeck effect. Many modules are connected in series or parallel. Water cooling is needed for the cold side and an inverter is needed to produce grid quality electricity. This technology has some advantages because it is similar to PV, a solid-state technology.

It can be constructed with ZnSb, Bi-Sb alloys or PbTe thermoelectric elements. According to past studies about the efficiency, it never reached 4%. The main energy losses are due to radiative and conduction losses. But new studies show more attractive results. Dent and Cobble [5A] used thermoelectric generators for solar parabolic dishes. Using PbTe elements, thermodynamic efficiencies of 4% at 510ºC were achieved. Good efficiencies can be achieved in the temperature range of 150ºC-250ºC, with Bi2Te3 materials [4A]. There is an optimal hot-side temperature that maximizes the efficiency of solar thermoelectric generators. It is a combination of the device efficiency and the opto-thermal efficiency. Currently, as a standard efficiency the value 5% is reasonable [6A].

This technology can be seen as a good option for small appliances in rural non electrified areas for installations below 1 kW [6A]. But inverters are needed, as the electricity generated is of DC current.

1.2 Market analysis

1.2.1 INNOVA

INNOVA, from Italy (Pescara and Cosenza), works since 2005 around the development and research of clean and distributed thermal energy systems. INNOVA has two products, Trinum and Turbocaldo. For these, a warranty of 2 years is given by the company [13B]. Both include an electrical and hydraulic switchboard, with pump.

1.2.1.1 Products: Trinum and Turbocaldo

Trinum is a 3.75 m diameter solar dish available since September 2010 which provides 1 kW electric power and 3 kW thermal energy. The electrical output power has 230 V and 50 Hz, and is produced through a small Stirling engine. This free piston engine is for exclusive use for INNOVA and was developed together with Microgen Engine Corporation. The average efficiency is 13.8% for electricity and 41.4% for heat. According to Mr. Maccarone from INNOVA, the price is € 21.000 for each single Trinum.

Turbocaldo is available since 2012 and provides 7 kW of thermal energy for hot water, space heating and cooling. Its efficiency is 10% higher than for a standard vacuum tube. The heat transfer fluid can be either water or a Propylene glycol-water solution. Its temperature can achieve 115ºC, but there are special versions providing up to 250ºC. The flow rate is in the range 7-19 l/min and the pressure can be up to 6 bar. According to Mr. Maccarone from INNOVA, the price is € 12.000 for each single Turbocaldo.

1.2.2 Literature, current developments and research projects

Beside INNOVA, there are currently no companies which sell commercial parabolic dish products for electricity generation. For the market analysis of this technology, this chapter shows firs two references with three simulations, and finally some details about other developments which are running now and which can possibly lead to new commercial products in the future.

There are two interesting studies about the economic feasibility of solar dish power plants in Algeria [1D] and [2D]. Three characteristic geographic regions are analyzed in each, and two are coincident. The first is Tamanrasset, which is in the extreme South of Algeria, and the second is Algiers, in the coastal region. The direct normal incident solar power in Tamanrasset is very high, the mean temperature is relatively high and it is a bit windier, when compared to Algiers. Details about the technological assumptions are briefly described in Table 1.

Each column describes one simulation. In the first, the EuroDish was used. It was the third prototype installed at the Plataforma Solar de Almería, with several improvements to its precedents, DistalI and DistalII [4D]. The second column represents an assumption of the mass production of 500 – 5000 units / year. The cost reductions were based on the estimations from Manuel, R. A., and Zarza, E. 2007 [3D]. Finally, the third study at the third column is based on an engine from SES. The results for both locations for all three studies are presented in Figure 4. It gets clear that the past engine model from SES and the commercial estimation have the best results. And it gets clear that the desert climate from the south (Tamanrasset) is more cost effective.

These results are not relevant in terms of technology, as there is no mass production of Stirling Dishes, the model from SES is not available any more, and the EuroDish is just a non commercial prototype.

Table 1 - Assumptions for enconomic analysis of Dish power plants for Algeria [1 and 2D].

	Year, source	2013, [1]		2010, [2]
	Technology	**Prototype EuroDish**	**Commercial estimation**	**SES model**
Receiver	Aperture diameter (m)	0.18		0.2
	Temperature (ºC)	780 – 800		720
Concentrator	Type	Single segment of fiberglass resin		Thin glass mirror
	Diameter (m)	8.5		10.57
	Projected area (m²)	56.7		87.7
	Reflectivity	0.94		0.91
	Concentration factor	9300		7500
Engine	Name	Solo 161 from EuroDish		Kockums 4-95 SES
	Power/unit (kWe)	10		25
	Size	4 cylinders 160 cc		4 cylinders 380 cc
	Working fluid	Hydrogen		Hydrogen
	Rotation speed (rpm)	1500		1800
	Min insolation (W/m²)	250 – 300		
Costs	Cost /kWe	14,000 € without foundations	1,125 €	2156 €
	Transport & installation	28,000 €/unit	2,250 €/unit	
	O&M cost	5 (% of total invest)	3 % of total invest	5 €/MWh + 36€/kW-year
	Lifetime	10	25	30
	Discount rate (%)	8 (by International Energy Agency)		
	Sale price (€/kWe)	0.45	0.45	0.13 $/kWh
	Land	offered by government		
	Taxes	ignored		

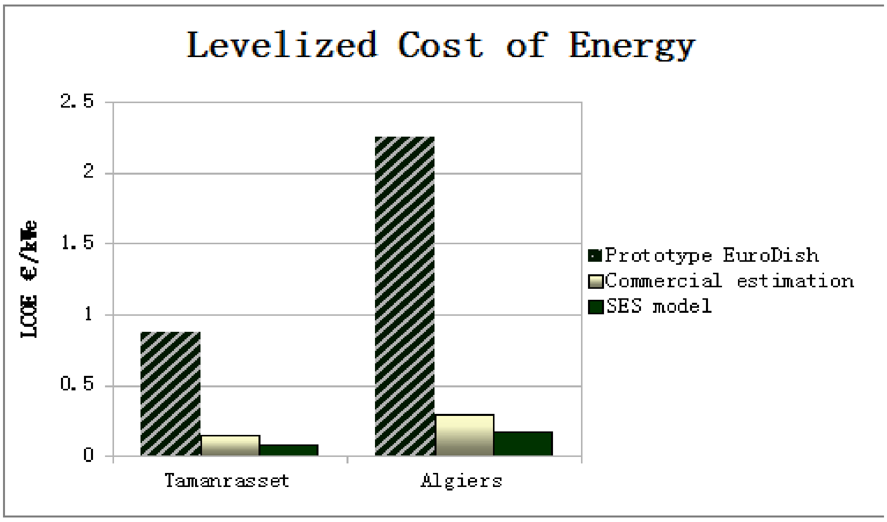


Figure 4 - Levelized cost of electricity for two sites in Algeria (Tamanrasset and Algiers) for three different dish technologies [1D and 2D].

1.2.2.1 OMSoP

The project OMSoP, Optimised Microturbine Solar Power system is part of the EU's 7th Framework Program for R&D. The total budget is of 5.8 M€, where 4.2M€ comes from EU funding [8B]. The main objective is the research, development, testing and production analysis of a solar dish system with units in the range 10 – 30 kW for small domestic and commercial applications and even large scale electricity production. The dish will not use a Stirling engine. Instead, it will use the Brayton cycle, having near the focus point a micro gas turbine. Storage solutions and integration of co-firing will be also analyzed. For the micro gas turbine it is easier to include hybridization comparing to Stirling due to geometrical constrains.

Three main "Work Packages" will be included, and for this, eight industrial or academic partners will work together. In the first "Work Package", a 10 kW system will be developed and constructed; additionally components for a 30kW model will be developed. INNOVA will be responsible for the solar concentrator, Compower for the micro gas turbine, KTH for the receiver and City University London for development and testing, through the principal investigator Sayma, Adbul Naser. In the second "Work Package" the whole system will be tested and optimized, and first economic data will be determined for further analysis. In the 3rd "Work Package" the thermodynamic and mechanical models will be optimized in more detail. Further analysis about storage solutions, power augmentation, hybridization and finally market, cost and environmental impacts are planned.

The project will be in the period 2013 – 2017 and involves a research and development period (2013/2014), a period for proofing the optimization of components (2014/2015) and finally a period to proof the whole concept through demonstration, after 2016.

1.2.2.2 BioStirling - 4SKA

In many countries of the southern hemisphere, for the Square-Kilometer-Array (SKA) several sensor-based infrastructures will be installed for radio Astrønomy starting from the year 2016. First observations are expected for 2017, and in 2025 the complete system is expected to be working. One third of the installations will be in Australia, and two thirds in African countries [11B]. This project, from SKA Organization will involve 67 organizations in 20 countries. They will have 1 km² of data collecting area connecting nodes of thousands of antennas. [9B]

These systems will have high energy consumption 24/7 while they scan the sky continuously. They use energy for operation, cooling, computing, telescope management and monitoring. As they will be built in remote locations, conventional diesel systems are not viable. One possible solution are Stirling dishes including bioenergy storage and hybridization.

The BioStirling-4ska project aims at developing and testing a total of 150 kW autonomous solar dish prototypes for 36 months. It will have a total cost of 6.3 million Euro, where 3.8 million Euro are financed by the EU 7th Framework Program in the area of Research, development and testing of solar dish systems. It will be located in Herdade da Contenda, Moura (southeast of Portugal), a region of low Radio Frequency Interferences and high solar energy levels comparing to the rest of Europe. The consortium includes three industrial companies (Gestamp Toughtrough and Lógica), three technological enterprises (Alener, Machttechnik and Cleanenergy) and research centers and Universities (JYI, CTAER, US, CSIC, AstrøN, IT, MPG and Fraunhofer) [12B].

A total of 15 prototypes will be installed, each with 10 kW. From these, five will include storage system, seven will include hybrid system running with biogas, and three will include both. Later, the problems about limited availability of energy storage capacity and variable solar energy are expected to be solved through a SmartGrid [10B].

According to Mr. Jimeno, the project started in June 2013, and "the consortium is defining the detailed technical solution and also considering the economic impact of each variation". But if the final product will be not only for SKA but also for commercial purposes, this is a target but will be analyzed when the project is in a more advanced state.

1.2.2.3 Qnergy

Qnergy was started in 2009 by Ricor Cryogenic and Vaccum Systems. After acquiring Infinia Corp assets, Qnergy decided to integrate experiences and know-how of both with the target of a mass production of Stirling engines. They also include Ricor's technology.

The main product they have enables decentralized power and hot water generation at 90% efficiency, near the demand which can be residential or business customers. The two free piston Stirling engines Qnergy offers can be applied in a wide range of applications such as micro-combined heat and power, solar power generation and solar CHP [3B]. The two models work with Helium as working gas in a closed engine. One provides 3.5 kWe and is recommended for solar applications or small residential MCHP. If it would installed with a solar dish tracking the sun, it could produce clean energy for any production scale. Together with Abengoa Solar, Qnergy is designing now a solar dish Stirling system. According to Mr. Dvir, as the PowerDishTM from Infinia is no longer available, “A new version is in development, and will be ready not before end of 2014.”

The second has 7.5 kWe and can be used for larger MCHP, biomass, oil and gas burning. Additionally, Ricor is developing a 400 W free piston Stirling model (FPSG) for small size electricity generation.

1.2.2.4 HelioFocus

HelioFocus is an Israeli company owned by the Israel Corp ICG, has been founded in 2007, and has been working on a specific solar parabolic model. They patented diverse intellectual properties, starting from the special parabolic dish, through the volumetric receiver, heat logistics and finally the system design.

The company has received financial support from IC Green Energy (Israel) and from Zhejiang Sanuha (China). In the system, hot air generation, super critical steam generation or direct power generation is provided by a parabolic dish. HelioFocus targets conventional utilities, developers, traditional power plant owners and thermo-chemical industry in any geographical areas with high radiation conditions. According to them, “Less than half the area is required for the same energy output, in some geographical locations.” [13C]

1.2.2.4.1 Products: HelioBoosterTM & EnergiXTM

The solar dishes from HelioFocus concentrate at the ratio 1:2000. This high concentration provides high temperature air as heat transfer fluid in the temperature range of 650ºC - 1000ºC. High working temperature ranges provide higher conversion efficiencies, according to thermodynamic laws. The heat is used to produce steam at 540 – 620ºC. Less civil works are needed as the land slope can be of up to 5%, which is not the case for other CSP solutions. No water is needed for cooling, because instead of conventional cooling towers, an air condenser is used. Even no oil as a heat transfer fluid is needed, only air. For production stability, an energy capacitor is used to compensate solar fluctuations.

The pressurized volumetric receiver is a product as a result of 20 years of research and includes insulation, a ceramic absorber, and a transparent element that seals the receiver volume. The parabolic dish (500m²) uses simple carbon steel elements and includes 2 axis tracking. Instead of being a curved parabolic, it is flat but the spherically curved solar mirrors are in an arrangement is like Fresnel mirrors [14C]. Using these components, two products were developed by HelioFocus, one for power plants empowerment (HelioBoosterTM) and one for standalone systems (EnergiXTM), which are presented at the Figure 5.

HelioBoosterTM product offers power enhancement for combined cycle power plants or coal power plants. This allows a reduction of emissions enhancing environmental profile of the operations of fossil fuel power plants. Small scale installations can have just 15 MW, large installations can have up to 50MW.

EnergiXTM is a standalone power generation system using a central steam turbine. The hybrid system with any fossil fuel for burning allows a 24/7 electricity supply. Also a reheat cycle is included for increasing efficiency. It is modular, so small off grid generation starting from 10 MW or even grid connected utility scale of up to 100 MW generation is possible. A 10 MW project for the location of Inner Mongolia, China, uses a land area of 120 000m².

According to Mandelberg, their products are not commercially available now, "We still need to get "bankability qualification"- system level in order to use banks financing for customer projects, I expect that our products -commercial financed- will be applied in two years."

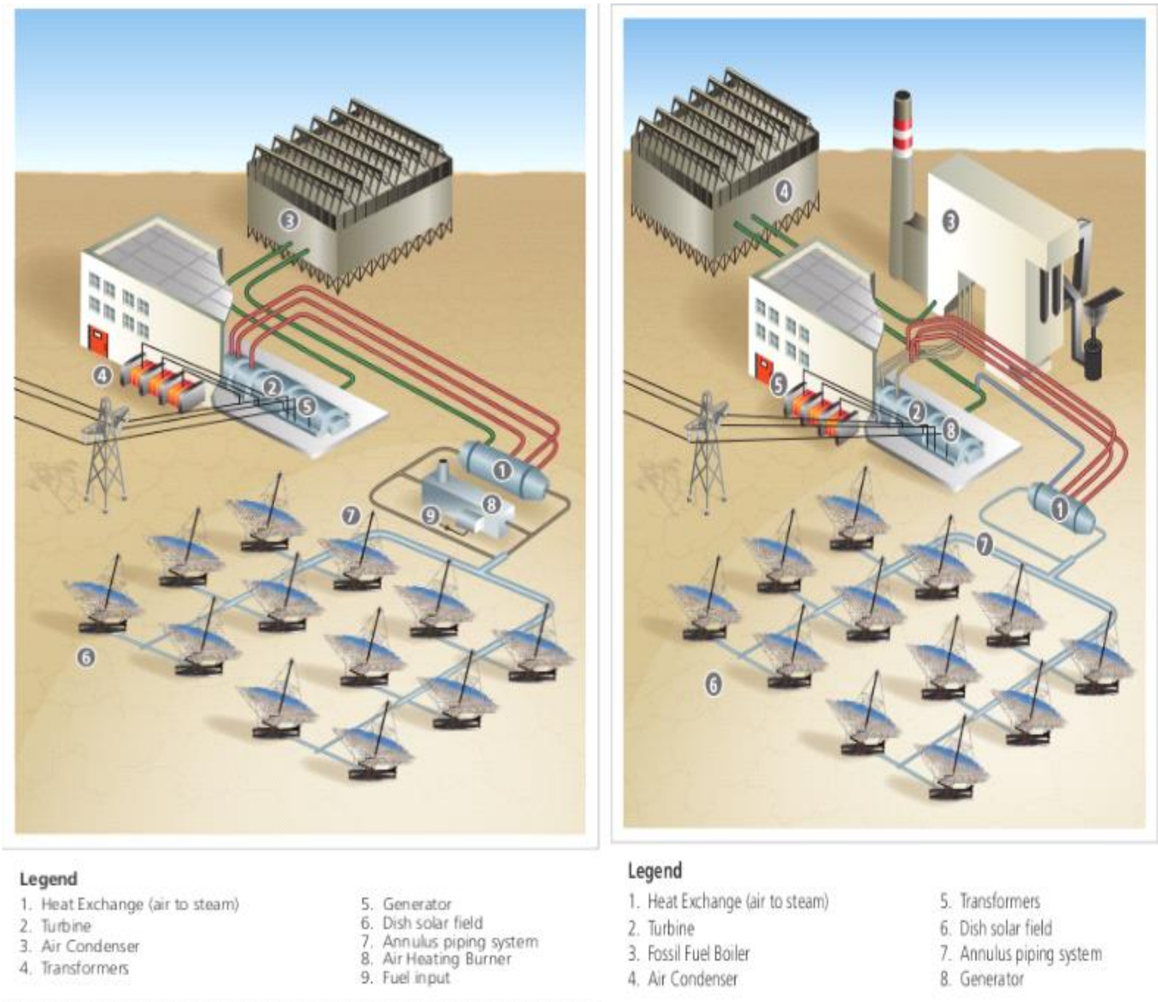


Figure 5 - EnergiXTM (left) and HelioBoosterTM (right side), Ref:.[13C], product brochures.

1.2.2.5 AirligthEnergy

Airlight Energy, from Switzerland, provides technology for large scale production of electricity using solar power and for energy storage, including CSP. Together with IBM research Zurich, ETH Zurich and Interstate University of Applied Sciences Buchs NTB, a new electricity generation based on the solar dish is being developed. It will provide 25 kWe [16B], desalinized water and conditioned air. 2000 suns are concentrated on triple junction photovoltaic chips, which convert the solar energy into electricity and heat. Through a microchannel cell cooling system this heat is transferred to another system, which can be an absorption chiller or desalinization system. To reduce the cost, a pneumatic mirror system was developed using stretched metalized films, hold by a concrete based structure. It is expected that the energy produced will reach LCOE lower than 10 cents per kilowatt hour. The budget of 1.8 million € was awarded by the Swiss Commission for Technology and Innovation [17B].

1.3 Existing power plants

Table 2 shows where the solar power plant projects are located. For the technology column, "Parabolic Dish" means that a technology different than Stirling engine is used. It can be seen that only one power plant actually exist and is in operation, in China. Unfortunately only few information is available about this power plant. At the same time, many power plants were planned but canceled. Further analysis is presented in the next sections.

Table 2 - Dish solar power plants: all plants over the world in different stadium. Ref: Based on CSP today, CSP world 11 (March 2014) corrected by further research.

Company	Name	Country	Power (MW)	Status	Technology
China Huaneng Group	Hainan Nanshan Sanya Pilot	China	1	Operation	Stirling
HF	Stardust	Israel	0.5	Construction	Steam
	BODE	Israel	10	Development	
	CART WHEEL	Israel	10	Development	
	Orion	China	1	Commissioning	
	ANDROMEDA	China	10	Design	
	COMET	China	100	Development	
	HOAG	China	200	Planning	
WRST	One Solar	India	1	Construction	
SES	Maricopa	USA	1.5	canceled	Stirling
	Imperial Valley	USA	709	canceled	
	Calico	USA	663	canceled	
Infinia	Tooele Army Depot	USA	1.5	canceled	
	Ennex	South Africa	20	Planned	
	Maximus	Greece	75.3	Planned	
	HelioPower	Cyprus	50.76	Planned	
Wizard Power	Solar Oasis	Australia	43.5	canceled	Steam
Renovalia	Several	Spain	<72	canceled	Stirling

1.3.1 Plants in operation

1.3.1.1 Hainan Nanshan Sanya Pilot

Figure 6 - Stirling dish power plant Hainan Nanshan Sanya Pilot [2].

As seen in the last table (Table 2), the only power plant that actually is in operation is located in China. The 1MW plant is installed in Sanya, province Hainan and has an area of 4 ha (Figure 6). The island is ideal for solar power projects due to the sunny climate and long days. The power plant was developed by Ecube energy and cost 4 million Euro. It was constructed by China Huaneng Group, one of the largest electricity producers in China. The government set policies and plans for this area on renewable energies to create a low-carbon tourism destination with international stature [3C]. The most visited tourist attraction in Hainan is the Nanshan Cultural Tourism Zone. It is owned by Hainan Nanshan Tourism Development Ltd [4C]. Environmental resources, investment and management is known to speed up profitability due to environmental friendly image, cost savings and rapidly growing visitor numbers. Actually there is very few information available about the power plant, which might be a sign that it actually does not work.

1.3.2 Plants in construction/planning phase

1.3.2.1 HelioFocus

The company HelioFocus from Israel is involved in three projects in their country: Stardust (0.5 MW), BODE (10 MW) and CART WHEEL (10 MW). Stardust is now being constructed in Ramat Hovav for Israel Electric Corporation (IEC). BODE will also be constructed at the same location and also for IEC, but is now just being designed. Both are for combined cycle boosting and the second is expected to enter into operation in 2015. The third project, CART WHEEL, will be constructed for Ofer Power Company till 2015 and is still in design status.

Additionally, this company signed together with Sanhua a Memorandum of Understanding in May 2012 about creating the first solar thermal power project for a Chinese Energy Company. Several power plant will be built with all components being supplied by HelioFocus. All power plants will be built for TAIQING Solar Thermal Power Co. The first power plant, Orion, is located in Inner Mongolia, China. This power plant is commissioning now and has a total power of 1 MW. The second, ANDROMEDA, will be constructed at the same location but it will be larger, with 10 MW of production. At the moment, it is being designed for being finished around 2016. Another project, COMET, with 100 MW is under development. The big target of this project is that at the end a big 200 MW power plant is designed, HOAG project. It will cost around $340 million. Through this, a solar city is planned to be built in the region [13C-15C].

The technology used is further described in the section above about the HelioFocus company.

1.3.2.2 One Solar Thermal Power Plant

One Solar Thermal Power Plant is a 1 MW project being built near the Shantivan Campus in Abu Road, Rajasthan (India). It is sponsored by the Ministry of New and Renewable Energy Sources (New Delhi, Government of India) and Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Berlin Government of Germany through GIZ).

It is being built by WRST, (World Renewal Spiritual Trust), which is a solar research center. First, a prototype was built and successfully tested. Now, more 770 Scheffler dishes of 60 m² are being installed with a total mirror area of 450000 m². The advantage of being a Scheffler dish is that the focus point is fixed so that no flexible high pressure joints are needed for direct steam generating mode. The steam turbine will work at 41 Bar and 255ºC. The plant will include 16 h of storage to provide continuous operation. Not only electric power will be used but also heat – high efficient co-generation near the consumer. At the moment there are actually several Scheffler dishes already being used at the same location for community cooking for many people. All this has the support of the Fraunhofer Institute and Wolfgang Scheffler. The total cost is ~11Mio € excluding cost of land. [16C], [17C]

1.3.3 Canceled power plants

It has been difficult for developers to commercialize the concept on a major scale. Some challenges are still to be solved. There is not the advantage of storage, when using directly a Stirling engine. So the big advantage of solar thermal technologies comparing to solar PV does not exist for the Stirling dish. Comparing now PV with the Solar dish, the first one is much cheaper and well tested. Additionally, the two axis tracking system for the dish still requires high precision that depends on moving parts, which requires maintenance and a good structural stability (costs).

According to Deign, J. from CSP Today [9A], the penetration of Stirling dish systems in the market was not well succeeded as expected. It has failed to make its mark in commercial terms. The opinions to explain the lack of success mention some technical problems related to the fact that the working cycle is closed, it has to be in a closed space to avoid leaks, which is still a great challenge [15B]. Furthermore the operation temperature is high as well as the pressure.

1.3.3.1 Stirling Energy Systems

Stirling Energy Systems (SES) was formed in 1996 in Arizona, and compiled from the engineering design up to power generation of SunCatcherTM. It acquired several patents about the solar Stirling technology, developed by Ford Advanced Development Operations, McDonnell-Douglas Aerospace & Defense and Boeing Aerospace & Defense. They build up a partnership together with Sandia National Laboratories, and United States Department of Energy. Their product was a solar dish with a 25 kW Stirling engine, which could have been used for small or large scale power plants up to 1000 MW. Unfortunately in September 2011 SES filed for Chapter 7 bankruptcy [1B]

Several power plants were planned but never built. In 2010, SES was asked to build together with Tessera several plants in USA: Maricopa (1.5 MW), Imperial Valley (709 MW) and Calico (663 MW) [9A]. But as SES filed for bankruptcy the projects were canceled and turned into PV projects [5C, 18C].

1.3.3.2 Infinia: Tooele Army Depot and two NER300 projects

Infinia Corporation developed and manufactured a special Stirling model, called “free-piston Stirling engine”. The working gas is in a sealed enclosure, so the working pressure can be higher without leaks. Additionally less moving parts are accessible and maintenance is not needed for longer periods. The engine could work with different heat sources, such as solar energy, biogas or natural gas.

For using the solar energy, Infinia developed PowerDish, which is a parabolic mirror with the Stirling engine near the focus point. These modular units could be used for small or large scale power generation plants [8C]. Small scale PowerDish units were installed around the world by Infinia [5C].

In the period of 2006 – 2010 Infinia installed about 100 systems [15B]. In the first half of 2013, Infinia got several new projects, including nearly 200 MW o projects in the Mediterranean region an the 1.5 MW Tooele Army Base power plant in Utah. Even in South Africa, Ennex Dish Stirling announced a 20 MW power plant using the PowerDishTM.

But Infinia was not able to create positive cash-flow and full-scale operations early enough, and with a leak of financing, it has filed for Chapter 11 on September 17, 2013. The first offer was by its lead lender, Atlas Global Holdings, which offered a price of $6 million, and the re-marketing process continued until October 31, 2013 [5B]. Finally, Qnergy has acquired Infinias assets.

1.3.3.2.1 NER300 projects, Helios Power (Cyprus) and Maximus (Greece)

The European NER300 project was created to support several new projects around innovative renewable energy technologies and carbon capture storage. The budget of 1.2 billion Euro was obtained selling carbon dioxide emission rights. Included in this project were two large scale Stirling dish power plants, one in Greece and one in Cyprus. In the beginning of 2013, these projects were given to Infinia Corporation but no recent information about the development is public available.

Maximus was to be built in the region Florina, North West of Greece. The power plant, from Maximus Solar Thermal LTD would have a rated power of 75.3 MW. A total of 25160 dish units with 3 kW each would build up 37 small power plants, together connected to the grid. The NER300 subsidy budget was € 44,550,000 and the plant was expected to enter into operation in June 2015 [19C] [5C].

Helios Power was to be built near Larnaca in Cyprus, with a total power of 50.76 MW. A total of 16920 dish units were to be installed on a land area of 200 ha. The NER300 subsidy budget was to be € 46,621,418, and in October 2014 the power plant was expected to enter into operation [5C], [9C], [20C].

1.3.3.2.2 Tooele Army Depot 1.5 MW, USA

Infinia made several attempts to install a large 1.5 MW solar dish plant in Tooele, Utah in the United States (40°19′ North, 112°18′ West). This power plant would have 429 units of the “Infinia Corp PowerDish(R), each producing 3.5kW with an efficiency of 34% [5C]. The closed loop free piston Stirling engines were designed to work with helium near the focus of a parabolic dish with 35 m² of aperture area and 6.4 m high [7C]. No storage would be included in the system, but no water would be needed, just for dish-cleaning purposes. The total cost would have been around US $8.7

million. The power plant would extend to 6.9 ha field. The aim of this power plant would be to produce electricity for the Tooele Army Depot, which also was its owner. The dependence on fossil fuel can be seen as vulnerability, and dependency on the national grid is not desirable [6C]. The demand is about 4 MW, and nearly 60% of its was expected to be produced by renewable energy, half of it through the Stirling/Dish plant, and half through a existing wind turbine [6C].

Infinia broke ground the power plant at 17 August 2012 ([9A]), but only started commissioning in the early summer 2013 [5C]. It was expected that the power plant would be of fast installation, and start its production in 2013 ([5C] and [6C]), but it didn't. But as Infinia field for Chapter 11, the project did not continue.

1.3.3.2.3 Renovalia

Renovalia had a project to install several power plants in Spain. The total power sum up to 72 MW. The CSP 3000 systems included 3 kW dish units with the free piston technology from Infinia. But as the technology provider was changed and the Spanish regulatory framework for CSP changed, the company canceled the projects. [22C], [23C].

1.3.3.3 Wizard Power: Solar Oasis

The development of the idea about this power plant started in 1994, where a large 400m² dish prototype was built as a result of researches by the Australian National University. The overall result was positive, but a more commercial design was needed. So a new 500m² so-called Big Dish (SG4) was designed and built up between 2008 and September 2009 with funding from Wizard Power and Australian Government Renewable Energy Development Initiative. The first sun test was in 29 June 2009. This 19.1 ton dish (plus 7.3t for base and supports) is actually formed by 380 small mirrors with each 1165 x 1165 mm and 93.5% reflectivity and is able to concentrate the sun 2000 times [11C]. The diameter is 25m and 13.4 m is its focal length. The high concentration shows the ability for high temperature processes such as power generation or even chemical reactions for fuel production. According to Lovegrove, K. et al [12C], “The dish will be used as a research tool to investigate energy conversion via direct steam generation, thermochemical processes for fuels and energy storage and small Brayton turbine cycles among others”. Even if the cost per unit area is higher than for other solar concentrating technologies, the optical efficiency and thermal efficiency are higher [11C].

“Whyalla Solar Oasis” is a consortium that was established by National Power and Sustainable Power Partners in Whyalla, South Australia. Sustainable Power Partners (SPP), National Power Pty Ltd and Wizard Power combine experiences in different areas. SPP is an originator and developer of large scale solar thermal and PV plants. National Power Pty Ldt is the main Australian company for the National Power Group and develop, own and operate renewable energy plants. Wizard Power commercialized, developed and market solar thermal technology [10C]. They own now the intellectual property of this BigDish and planned to develop a 43.5 MW power plant for generating 66 GWh/y with 300 BigDish units. The power plant was expected to build 200 jobs in the Whyalla region and initiate high tech facilities. As a second stage, a 200 MW solar power plant was planned. The total value for the first 40 MW plant was $230 million, from which $60m were expected from the federal government. But the Australian Renewable Energy Agency pulled the funding, because the conditions of the agreement were not met [21C]. Now Wizard Power is in the hands of an administrator, and the project was canceled.

2. Parabolic trough

Parabolic trough power plants were first patented in Stuttgart in 1907. Parabolic trough power plants use, as the dish technology, a large area of mirrors to concentrate sunlight which is used as a heat source. Instead of point focusing, the solar field consists on line focusing arrays.

Parabolic trough is the CSP technology which has the oldest commercial plants, operating for almost 30 years. Several SEGS power plants in California proved the reliability of this technology as a long term investment [11F]. Comparing to the parabolic dish, this technology is in a much more advanced state. Large powerplants have been constructed and operated for several years all over the World, especially in Spain and the US. Even the literature provides broad analysis about specific technological aspects, improvements, and even financial analysis for different areas. Due to this advanced state comparing to the solar dish, for this technology a specific financial analysis was developed in this work. For the location, Morocco has been chosen as it is a country with good conditions for CSP regarding the solar resource (Figure 7) and it is in a relatively stable political situation. Additionally, the demand for electricity is increasing and the government has shown interest in CSP projects.

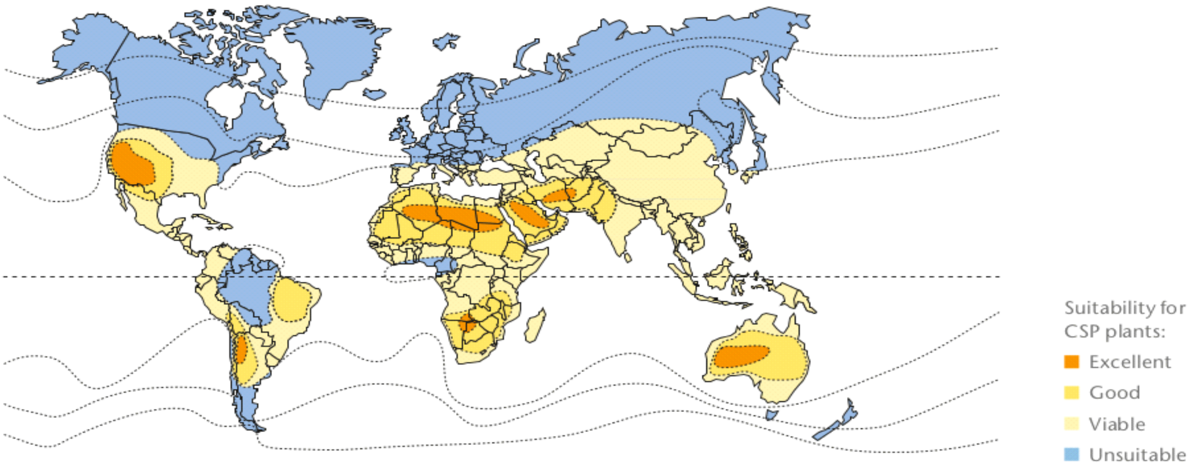


Figure 7 - Suitability of CSP power plants all over the world [11F].

2.1 General analysis of the technology

Solar parabolic trough fields convert solar radiation into heat through an array of line concentrators. This heat can be used both for electricity generation and directly for industrial process steam. For electricity generation, the heat is transferred to a power block where a steam cycle and electric generators convert the thermal energy first into mechanical energy and finally into electricity. This process is quite similar to conventional steam power plants, with the main difference being the heat source which is the sun, an emission free and clean heat source.

The solar field concentrators track the sun during the day and concentrate sunlight onto a receiver. Here the radiation is absorbed and the generated heat is transferred to a heat transfer fluid (HTF). The HTF is pumped in a closed piping system and flows inside the receiver tube. This way the heat is transported to the heat exchangers to produce steam in the power block or industry.

The suitability of parabolic trough power plants depends not only on the location but also on the size. Large-scale power plants (10 - 300 MW) are seen as being the most suitable option for this technology, being installed in the different regions over all continents, North-America, the desert regions of Africa, the southern region of Europe, Asia and Australia [3F], [6F]. One main challenge for CSP steam turbines are daily starts and stops created by the variable solar resource. To overcome this problem, and to generate reliable power for the grid, storage and hybridization are options which have shown great success. The possibility of thermal storage is actually the greatest advantage of CSP comparing to solar photovoltaic plants.

2.1.1 Hybrid power plants

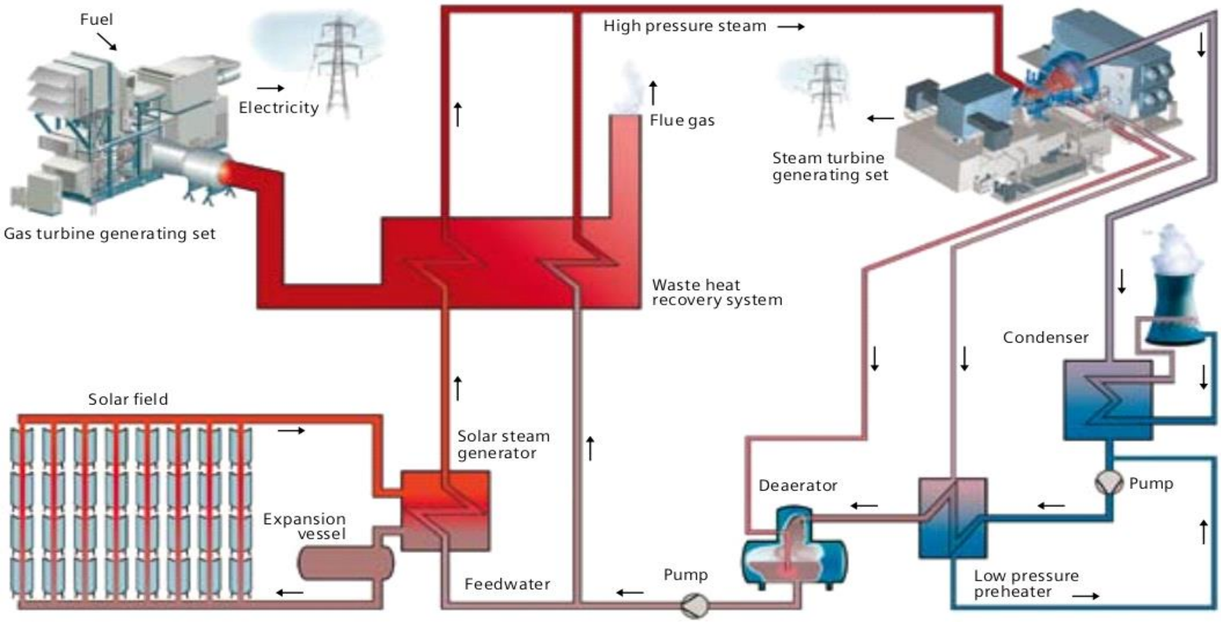


Figure 8 - Hybrid parabolic trough power plant [6F].

Conventional power plants can have a solar field attached to save fuel while producing the same amount of electricity (Figure 8). As a result the emissions per generated kWh generated decreases at the one hand, and at the other hand the solar field gets economically more attractive. For solar operation, the heat is used for steam generation, so that the oversized turbine operates with an increased amount of steam. [6F].

2.1.2 Storage

With storage, it is possible to provide thermal energy to the power block after sunset or when solar resource is variable. This means that if the CSP power plant includes a storage system, it is a stable electricity supply for the grid like the conventional power plants, and can help to balance the power supply grid. The main thermal storage technology used in CSP plants are molten salt tanks. Thermal storage is more cost efficient than electricity storage [3F]. Capacity factor with storage is up to 70%, but only 25% without.

Two-tank direct: This technology uses the mineral oil heat transfer fluid directly from the solar field piping system to store energy in unpressurized storage tanks. It was used by SEGS I, but newer power plants having higher working temperatures use an eutectic mixture of biphenyl-diphenyl oxide as heat transfer fluid in the solar field. To store energy with the same fluid, which has high vapor pressures, would require pressurized storage tanks which is not feasible for large scale.

Two-tank indirect: This is the most recent and widely used technology. The heat transfer fluid runs through a heat exchanger (see Figure 9) where cold molten salt from the cold storage tank is heated up. The hot molten salt is stored in the hot storage tank for being used later in the other way round, this time heating up the heat transfer fluid providing heat to the power block. The main disadvantage of this technology is the additional cost of the heat exchangers [1E]. To overcome these costs, it is also possible to use molten salts not only in the storage system but also in the solar field. But as molten salts have high freezing temperatures (120 - 220ºC), the entire solar field has to maintain at least this temperature level, which can be difficult at nighttime. New salt mixtures with lower freezing points are currently under research.

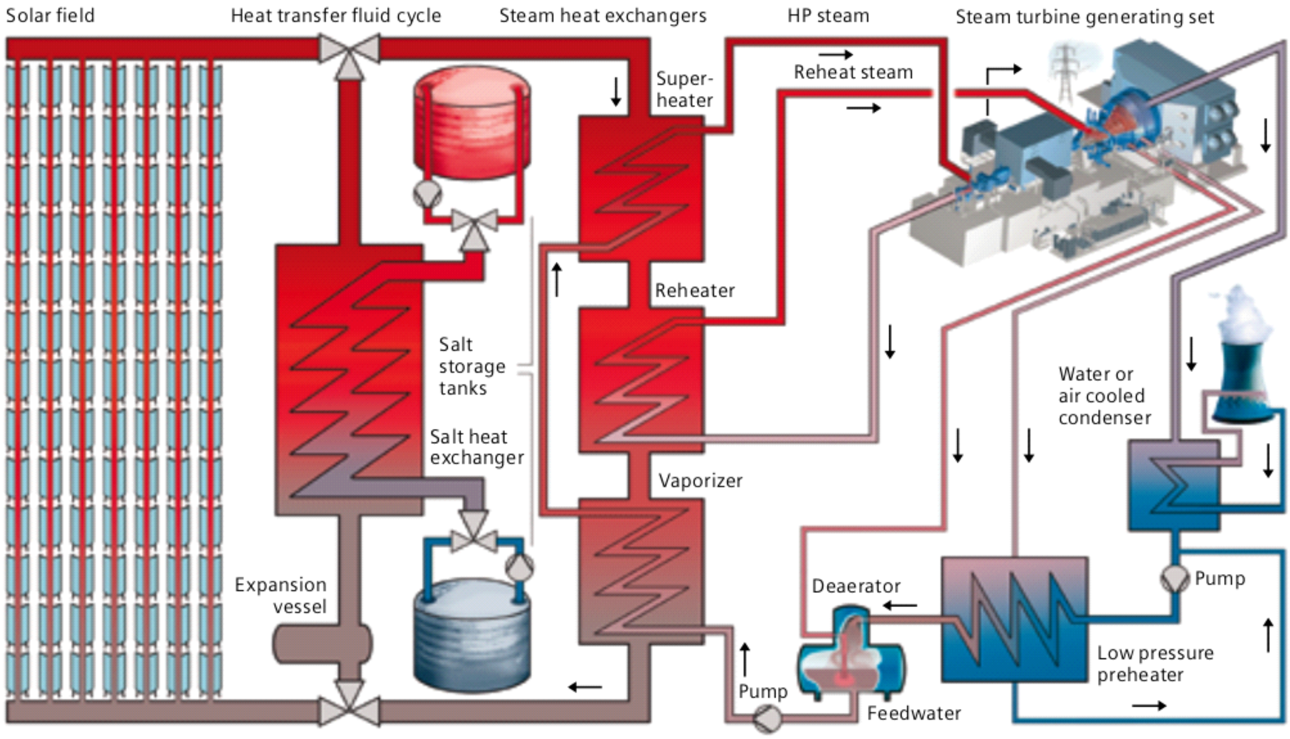


Figure 9 - Sheme of solar parabolic trough power plant [6F].

Single-tank thermocline: This technology is an alternative to the two-tank indirect thermal energy storage systems. The main difference is that both, cold and hot molten salt are stored in the same tank divided by a so-called thermocline zone, the hot molten salt placed on top. The tank can also include filler material such as sand or quartzite rock, which reduces the cost.

Concrete: Solid thermal energy storage media can be used to store the sensible heat. Here the heat transfer fluid passes directly through the storage media, transferring its heat. Research results show that concrete and castable ceramic materials can be used, but the first one has lower cost and is stronger. Main challenges are related to the contact between piping and the solid medium, as well as heat transfer rates.

Sand: Using sand as heat storage media is a new option which is still under development. One research project in the United Arab Emirates (Sandstock) and one research project in the US (US Solar Holdings, “SandShifter”) are developing technologies which will use sand as a heat collector, heat transfer and thermal energy storage media. Sand can be heated up to high temperatures, and it’s easy to move by gravity, but some technological and financial challenges keep these technologies at research level [2E].

Phase-change materials: To store thermal energy as latent heat has the advantage of reducing the medium volume. Different phase change materials melt in a per-defined sequence. Disadvantages such as the complexity of the system, thermodynamic constrains and few experience with phase-change materials keep this technology still at the research level [1E].

2.1.3 Solar field

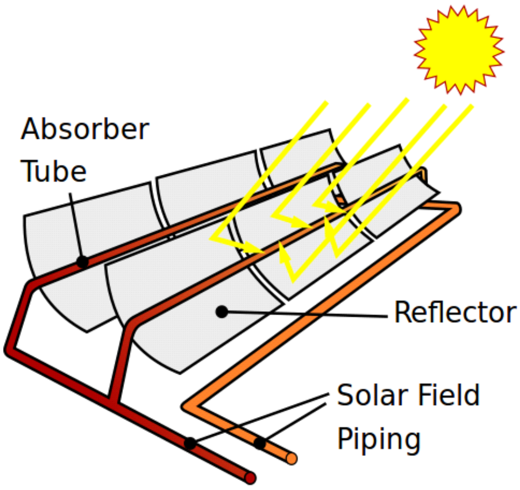


Figure 10 - Solar field - parabolic trough power plant [3F].

The solar field consists of an array of solar collectors (Figure 10). These focus the solar radiation on a line, where the absorber tube - the receiver - absorbs the radiation and transfers it to the heat transfer fluid flowing through it. The solar collectors are parabolic shaped mirrors which have its axis aligned in the direction North-South. This is the most chosen direction because the long arrays of collectors minimize the so-called cosine effect and end losses - losses due to the smaller incident power per area for inclined sunlight and the radiation losses at the border from the last collector which does not reach the receiver.

The first power plant, built in California, were supplied with collectors produced by Luz (Ls 1/2/3). Nowadays there are several companies supplying collectors, including Sener (SenerTrough), Abengoa Solar (Astrø) and Flagsol TSK (Skal-ET, or the optimized model HelioTrough). The structure has to support precisely the mirrors and the absorber tube. It has to be resistant to external forces such as the wind and the tracking system directs the parabolic shape to the sun, starting from Sunrise and ending at Sunset. Therefore three main types of structures have been used, the torque box, the torque tube and the space frame (Figure 11). These three types of collectors are dominant through most available and developed models as can be seen in the diagram (Figure 12). More details about the companies involved are available in the market analysis section

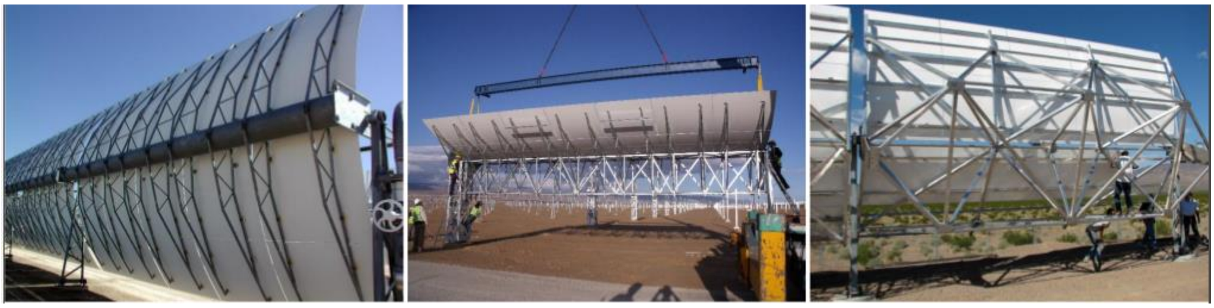


Figure 11 - Three types of collectors: torque tube, torque box and space frame [8E].

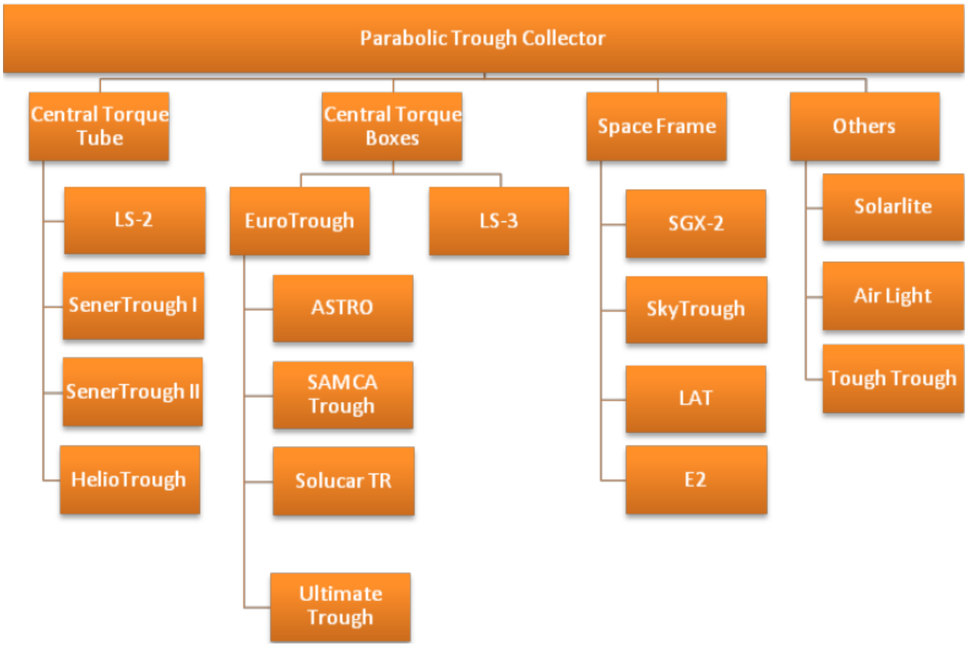


Figure 12 - Different parabolic collector models [8E].

The receiver is a steel tube with an optically selective coating. It absorbs as much radiation in the solar spectrum as possible (about 96%) and only emits very few in the infrared wavelength (about 9%), which reduces radiative losses. Additionally this tube is placed inside a vacuum tube (Figure 13). These have anti-reflective coatings to allow as much concentrated sunlight as possible to pass through the glass and reach the absorber tube (about 96%) [8E].They usually have diameters of 70-90mm.

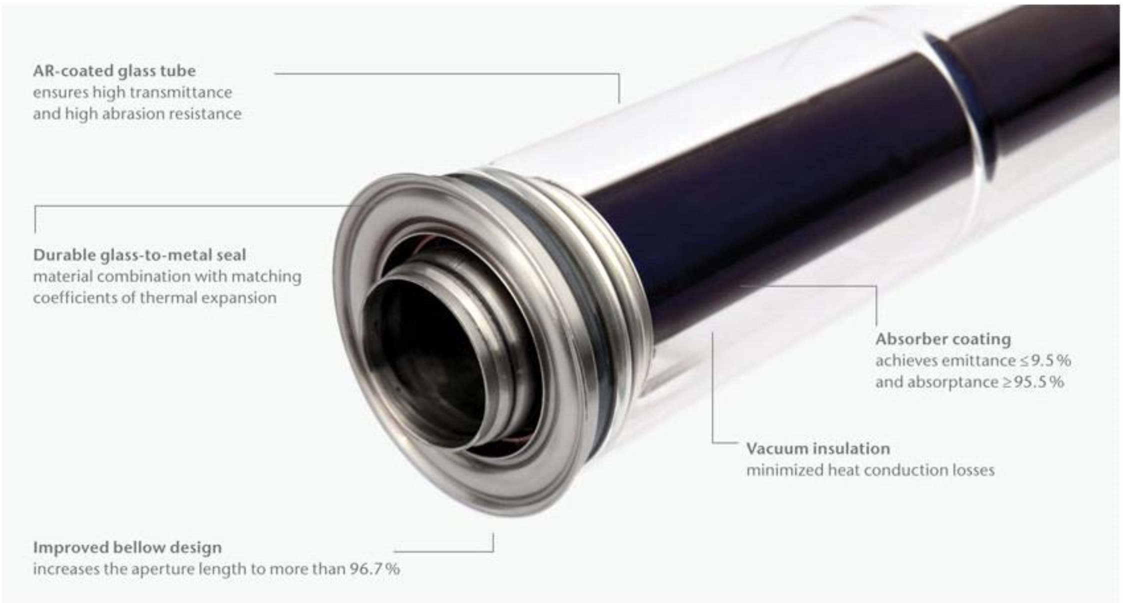


Figure 13- Receiver Schott PTR®70 [11F].

2.1.4 Heat transfer fluid

The HTF (heat transfer fluid) absorbs the heat from the receiver pipes and transports it until the heat exchangers in the power block. As the achieved hot temperature defines the efficiency limit of the Rankine cycle, the higher the temperature at which the heat transfer fluid operates, the higher the electricity output. There are three main types of HTF: synthetic oil, molten salts and water/steam. Most power plants opted for synthetic oil, and until now it is the best proven choice. Suppliers such as Solucia and DowChemical offer diphenyl/biphenyl oxide heat transfer fluids - Therminol® VP-1 and Dowtherm A. Its freezing point is at 12 ºC. To avoid freezing during nighttime and winter, the oil keeps running in the pipes of the solar field. Losses are not that big since the evacuated space around the receivers and the whole isolation protects the oil from heat losses, but if the oil would not continue to flow, leakages and isolation damages could be problematic cold spots [11F], [3F].

Unfortunately the oil operates in a stable condition only up to just 400 ºC, which sets an upper efficiency limit. To overcome this problem molten salts have been used as a second option. Molten salts are even cheaper than synthetic oil, and despite using more costly HTF system components, LCOE can be reduced by 10%-15% [6E]. Examples are the Solar Salt (60% $NaNO_3$, 40% KNO_3), Hitec (7% $NaNO_3$, 40% $NaNO_2$, 53% KNO_3), Hitec XL (48% $Ca(NO_3)_2$, 7% $NaNO_3$, 45% KNO_3) and other nitrate mixtures. The range of temperature increases to up to 450ºC - 500ºC, which rises the potential Rankine cycle efficiency to more than 40%. The 5 MW Archimede power plant in Italy used molten salts, but no larger scale power plants have until now used this technology. The high freezing point (87 - 130ºC for HitecXL or higher, for the other ones) is a challenge, but continuing with the appropriate insulation and evacuated tubes, the main challenge is actually to show reliability for financing in large scale power plants.

A third HTF type is to use simply water/steam. Direct steam generation rises the hot temperature up to 550 ºC. Less energy is needed for pumping, the initial investment for expensive synthetic oil is avoided, and actually the technology was successfully demonstrated at the Plataforma Solar de Almería (project DISS I+II). But the main conclusion of this project was that this technology is relevant for enhanced oil recovery and steam augmentation but not that much relevant for power generation.

2.1.5 Power block

When the heat transfer fluid reaches the power block, it provides heat through a heat exchanger to the Rankine steam cycle. The required hot temperature is defined by the heat transfer fluid used, and the cold temperature depends on how the cooling system is working. Between these two temperatures, a conventional turbine converts the temperature difference into motion, and the electric generator, which is coupled to the turbine, converts it into electricity. Existing power plants usually opted for turbines from the companies MAN or Siemens (specially the SST-700 model).

2.1.6 Cooling system

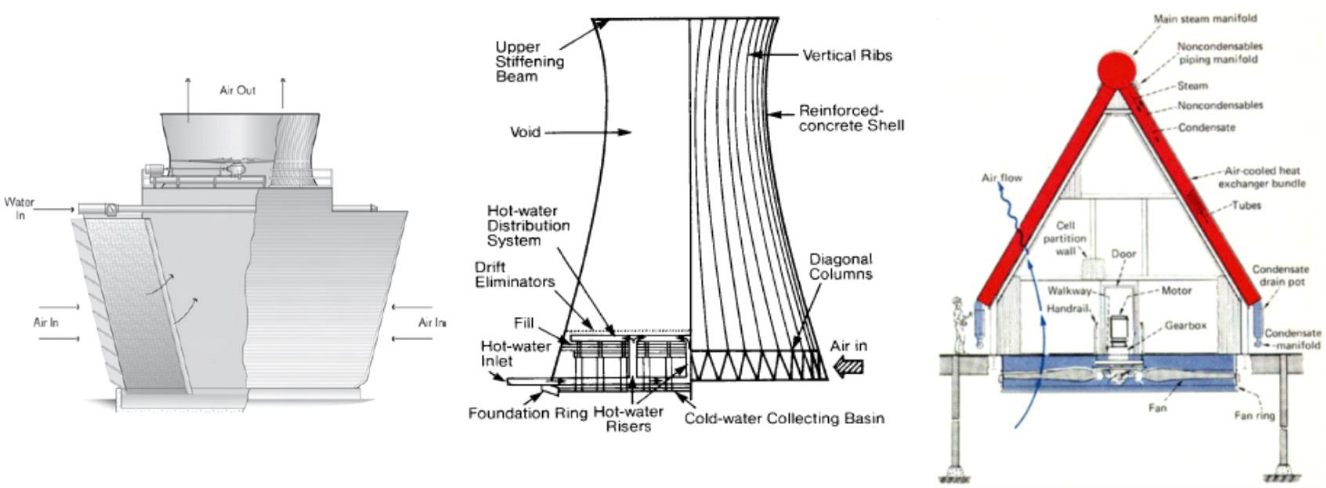


Figure 14 - Cooling systems: mechanical draft [3E], natural draft [4E], and dry cooling [5E].

There are two main types of cooling systems. The conventional one, also used in conventional electricity power plants, is wet cooling. Here, the hot steam flowing out of the steam turbine rejects its heat and part of the water evaporates. In mechanical draft towers there are large fans creating air circulation where the water is spayed or dropped (Figure 14, left side). In natural draft tower the difference of temperature inside the concrete tower and outside the tower creates air exchange (hot air with vapor moves up out of the tower, fresh ambient air comes in to the tower from the bottom - Figure 14, center). Wet cooling towers is the technology mostly used. But, as this technology wastes huge amounts of water in desert regions, a dry cooling system - air cooled condensers - has appeared as second choice, reducing water demand by about 95% [3E] (Figure 14, right side). In this case, there is no contact between the condensate and the air, the steam passes through air cooled finned tubes. Higher air flow and surface increase heat transfer rates. Hot sunny days present the worst situation for such a cooling system. As the cold temperature of the Rankine cycle increases, the efficiency drops as it is per-defined by thermodynamics and the Carnot efficiency. A larger turbine and solar field could overcome this efficiency loss, or an alternative wet cooling tower could be used for especially hot seasons. But with two systems, the cost increases, so that hybrid cooling is usually not economically feasible for most sites.

2.2 Market analysis

As the capital investment needed for a large scale parabolic trough power plant is still high, several companies are involved in many parts of the value chain, starting from technology development and research, through O&M services, EPC and ownership. This technology can still be called a recent technology. The tendency has been that some large industrial energy companies have opted to open their engineering skills to this new area, offering EPC services as well as developing their own collectors. The next list shows dominant companies from all over the world in the parabolic trough market, the order follows the alphabet. Some details about which products and services they offer are described shortly.

2.2.1 Abantia

Aplicaciones Generale Eléctricas was founded in 1944, focused in engineering, planning, development and installation of different industrial systems. Starting from 2006, it became known as Abantia, and beside the activities in many areas, the company is also became active in the thermal concentrated solar power. This includes services such as EPC, O&M and assembly in the energy sector [9F].

2.2.2 Abengoa

Abengoa has many energy-related activities, such as selling and producing renewable electricity, research, engineering and construction of environmental and energy infrastructures for third parties. The areas where they work is in Spain, USA, Brazil, the rest of Europe and even Africa. These projects include biofuel plants for the conversion of biomass into biofuel, large scale water desalination for drinking water production from waste and sea water, construction of electricity transmission lines and finally electricity production power plants. The electricity production plants are solar-thermal plants, solar-gas hybrid plants or even conventional generation plants. [1F] Abengoa developed 17 CSP plants, including several solar-thermal trough power plants in the USA, Abu Dhabi and Spain, such as Helioenergy 1/2, Solonova 1/3/4, Solaben 1/2/3/6 and Solancor 1/2. They also drived a 6h molten salt storage pilot system in the USA (TES pilot plant). Their 6 desalination plants work with take or pay contracts, with public water management companies from Spain, Algeria, India and China. The total production is 610 000 m³/day, and more 260 000 m³/day are under construction in Algeria and Ghana. Its engineering and construction division goes under Abener company. Beside conventional generation and biofuels, their business areas include solar electricity generation plants such as tower, parabolic trough and hybrid solar combined cycle plants.

2.2.2.1 Products

Collector: Astrø and E2Trough (Figure 15) are available for third party use. These can be purchased together with mirrors and absorber tubes.

Figure 15 - E2Trough collector from Abengoa [8E].

2.2.3 Acciona Solar Power

Acciona Solar is a Spanish company which leads with wind power, CSP, photovoltaic, biomass and hydropower. They design and manufacture components, develop and construct projects (EPC), and offers O&M for power plants. They also lead with marketing of energy and carbon credits. Their first power plant was the Nevada Solar One in the USA. After, ACCIONA Energy invested in five 50 MW plants in Spain. They entered into operation in the period 2009 - 2012 [8F].

2.2.4 Cobra

Since 1944, Grupo COBRA develops, builds and operates different industrial infrastructures, including solar thermoelectric power plants - parabolic trough and concentration tower. Cobra developed several solar through power plants with molten salt storage tanks in Spain such as the Andasol 1/2/3 plants, Extresol 2/2/3, Valle 1/2 and Manchasol.

2.2.5 GlassPoint

GlassPoint designs, manufactures and installs parabolic trough plants which produce steam for oil recovery. Glass Point was the technology provider for an oil recovery plant in California (300 kW) which was commissioned in 2011. Later, in 2013, they provided the technology for a larger plant in Oman (7MW) producing 50 tons of steam. The heat transfer fluid is water/steam, which is injected into the soil, the same way as common gas-driven oil recovery systems. The solar field is located inside a glasshouse, to protect the collectors from sand and storms. The integrated cleaning systems of glasshouses make cleaning easy and cheap. Their scope is not to produce electricity, but the glasshouse seems to be quite interesting even for electricity power plants in desert areas, like in Morocco.

2.2.6 Idom

Idom is active in different sectors such as Oil and Gas, Industry, Stell, Environment and Renewable energy. They offer engineering services such as planning, feasibility studies, conceptual design, basic and detailed engineering for EPC contractors. They participated in basic and detailed engineering of several operating power plants in different countries such as Spain, India and USA.

2.2.7 Ingemetal Solar

Ingemetal Solar was created in 2006 as a part from Ingemetal Group. They have developed and industrialized the parabolic cylinder fabrication process. Ingemetal designs new concentrated collectors to reduce cost and increase efficiency.

For La Florida and La Dehesa, two solar parabolic trough power plants in Spain, Ingemetal designed a trough collector, SAMCA-Trough model for SAMCA which developed, owns and operates these two plants.

2.2.7.1 Products

Ingemetal build a fabrication capacity for several metal components for the thermo solar industry, such as the parabolic collector metal structure. They fabricate whole parabolic cylinders, and build the necessary assembly plants, exterior facilities, manufacturing tools and equipment.

2.2.7.2 Services

Their services are mainly the transport of collectors to the site, topographical checks of the foundations, mounting and alignment of regular and director pillars, final installation of the collector and torsional leveling of the solar collector assembly. The service includes also the heat transfer fluid system mounting [7F].

2.2.8 Lauren Engineering

Lauren Engineering offers engineering, procurement and construction services in the US, Canada and India. The markets where they are active is not only solar power generation, but also conventional power generation (oil and gas), refining, metals and mining, chemicals and polymers. In the past, they were responsible for the EPC of parabolic trough projects such as the 72 MW Nevada Solar One and the 75 MW Marting Next Generation Solar Energy Center.

2.2.9 NextEra

NextEra operates wind, natural gas, solar and nuclear power plants, mainly in the United States and Canada. Solar facilities including PV sum up to a capacity of 575 MW, which is about 1% of the whole capacity from NextEra. NextEra is the co-owner and operator of all SEGS in the Mojave Desert, except SEGS I and II, which are from Cogentrix Energy trough. They also developed together with Genesis Solar the 250 MW genesis solar energy project.

2.2.10 Rackam

Rackam, located in Canada, is a company which developed and produces parabolic trough collectors. The model IRACUS HEAT builds 30 kW rows for medium temperature heat. It includes all components like the vacuum tube, a tracking system and supports. For the HTF, it could use thermal oil up to 220ºC or a pressurized water/glycol mixture up to 150ºC. The scope is to provide heat for food industry and other industrial processes. The relatively small rows can be mounted on ground or the roof. In July 2013 larger ground mounted version, S20, was announced [10 F].

2.2.11 Schott

Schott AG was founded in Germany in 1884, develops and produces special glass products. In the CSP market, Schott develops, designs and manufactures receivers. In the past they supplied many receiver tubes all over the world in large scale CSP power plants, to more than 50 projects.

2.2.11.1 Products

Receivers: Schott's receiver tubes can be used for both, parabolic trough and linear Fresnel CSP collectors. They cared specially for a reliable glass to metal seal, and include a hydrogen absorber for longer vacuum lifetime. Three main products are available:

> Schott PTR®70, which is the reference product. It was developed for oil based HTF. Its absorptance is higher than 95%, operation is at temperatures up to 450ºC and losses are lower than 250 W/m (tests in cooperation with NREL and DLR at working temperature). The receiver is 4.060 m long at ambient temperature. It can be seen in the Figure 13.

> Schott PTR®70 Premium, which is like the reference product, but integrates a "Noble Gas Capsule" which when it is activated, releases noble gas into the receiver reducing thermal losses created by the hydrogen which entered the space with the time. This leads to longer lifetime with good thermal properties.

> Schott PTR®70 Advance, which was developed to be used with 550ºC molten salts. It is quite similar the reference product, but is adapted for these working temperatures and includes a new absorber coating.

Receiver protection: This product was developed in order to protect the glass to metal seal of the receivers from solar radiation and at the same time to redirect the radiation to the active receiver parts.

2.2.12 Sener

SENER Group focuses not only on Aerospace Engineering, Marine, Infrastructures and transport, but also on power a process projects. These include different conventional types of power plants but also solar-thermal power plants. Their main services are the design, development and construction of solar CSP power plants (trough and tower receiver), supplying components, engineering services and project management. Their experience started with their first heliostats in the 1980s, which are now operating at the Plataforma Solar de Almería.

2.2.12.1 Products

Collector: Their new 13 m long collector SenerTrough shows improvements in the cost/benefit factor, the cost reduced and the size is 25% larger comparing to previous models (Figure 16). Some elements are made out of carbon steel, and the arms which connect the torque-tube to the mirrors are longer. A complete loop is in operation in Valle 2 thermosolar field. It was designed to work with the heat transfer fluid thermal oil.

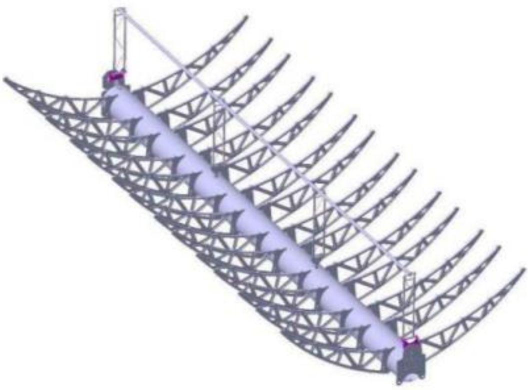


Figure 16 - SenerTrough collector model from SENER [8E].

2.2.12.2 Services

SENER Ingnería y Sistemas S.A. is the engineering and construction arm from SENER Group. The main areas of scope are infrastructures and transport, aerospace engineering, power and processes and other engineering areas. SENER has engineering teams specialized in relevant disciplines for the design, construction and O&M of a solar thermal power plant. According to their website, "Our services include all of the possible engineering and construction operations such as: feasibility and conceptual design studies, facility basic and detail engineering, procurement, work supervision, start-up, training of personnel, construction and construction management as well as EPC projects" [4F].

2.2.13 Siemens

Siemens acquired its know-how from the Solel Solar Systems company, plus the specialist Archimede Solar Energy. During the construction of the power plant Lebrija 1 in Spain, which was being build and the materials provided by Solel, Siemens acquired the company.

Siemens offers several services (installation, commissioning, repairs, EPC and O&M) and products related to CSP solar power generation. Especially their steam turbines are benchmark products (see below).

2.2.13.1 Products

Siemens is well known for the steam turbines, which are actually used and in operation in many CSP power plants. Beside solar receivers, the complete components for a steam/water cycle power block are available.

Steam turbines: As can be seen in the Figure 17, Siemens provides different turbine models for CSP plants. The turbines have a wide steam flow range to better adapt to the variable solar resource. They can operator in non-reheat, single reheat and double reheat cycles. A rapid start up and shut down time is very important for solar applications. Beside solar combined cycle power plants, the turbines can be used for steam cycle power plants. There are some smaller models, such as SST-110 and 120, but also very large ones such as SST 900, which can produce more than 250 MW. SST - 600 is specially adapted for tower technology and SST- 800 is specially adapted for direct steam generating CSP.

Special attention should be given to the dual-casing model SST-700 which is specially adapted not only for combine cycle power plants, fossil fuel steam plants, waste-to-energy plants, district heating plants, the oil and gas industry and industrial plants, but also for solar CSP trough technology (Figure 18). It was used in many solar power plants currently in operation in US, Spain, Germany and northern Africa. It was developed for producing up to 175 MW of output power. It includes two different turbines, one low pressure turbine and one high pressure turbine. For rapid starts, instead of the high pressure turbine, a high-pressure/intermediate pressure turbine can be used [6F].

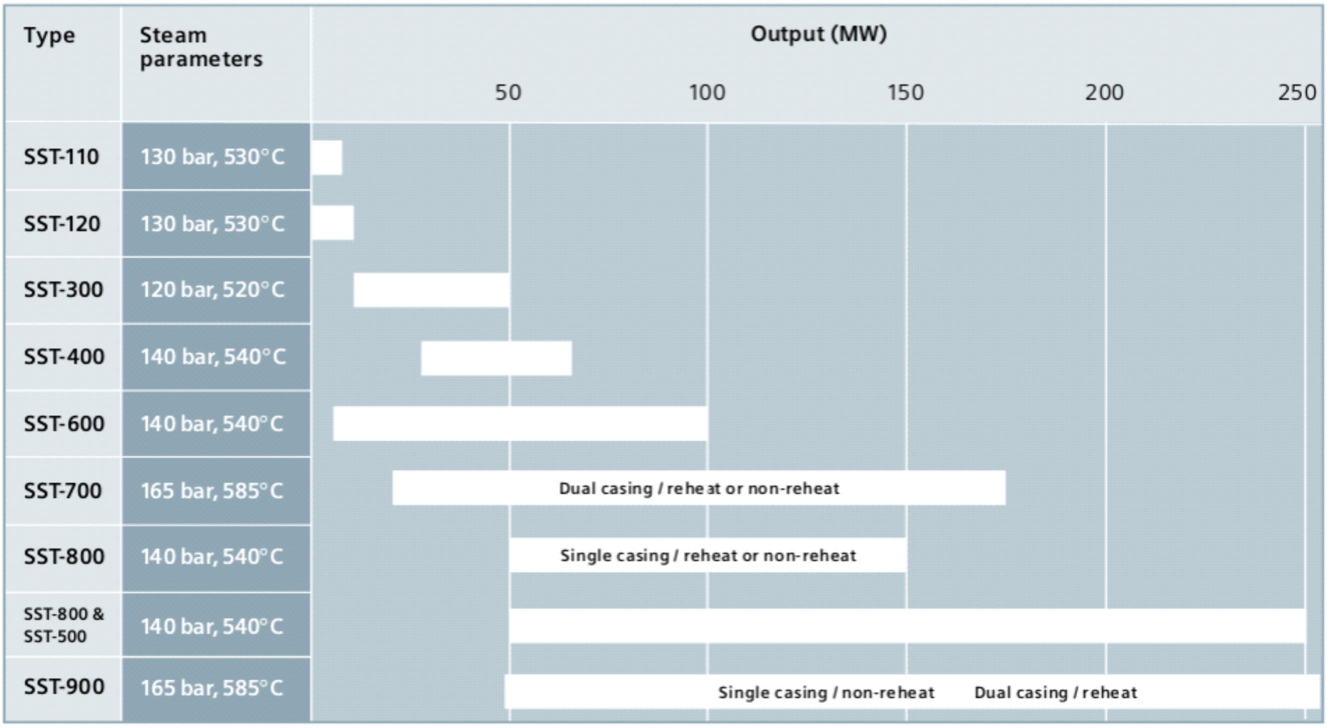


Figure 17 - Steam turbines Siemens [6F].

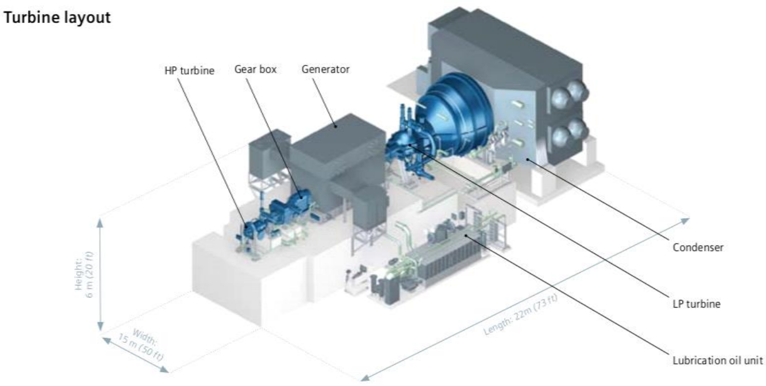


Figure 18 - SST - 700 steam turbine [6F].

Power block: This power block includes several key components manufactured by Siemens, including Siemens "BENSON® once trough" boiler, steam turbine generators, condensing systems to preheaters, evaporators, cooling systems, electrical equipment, plant control systems (Siemens SPPA-T3000), instrumentation, transformers and switchgears.

2.2.14 SkyFuel

SkyFuel was founded in 2007 with the main objective to develop and manufacture parabolic trough collectors. They supply their products to EPC companies (see below).

2.2.14.1 Products

Collector: SkyTroughTM is a parabolic trough collector for large scale solar thermal power plants and industrial process heat. It is 115 m long and has 6 m of aperture width. It uses OnSunTM as tracking system and the mirror film ReflecTech®PLUS instead of glass mirrors, which is lighter. Instead of steel torque tube or torsion box design, the collector uses lightweight aluminum space frame. Thermal efficiency data resulting from onsite tests is 73%. The product is available around the world.

Tracker: OnSunTM is a sun tracking system which positions the parabolic collector to the sun using a hydraulic rotary actuator from Helac Corporation. It includes the SkyTrakkerTM control system which calculates the position of the sun. A digital inclinometer technology tracks the sun within 0.06 degrees.

Mirror film: The ReflecTech®PLUS is a mirror film developed by ReflecTech, Inc., Red Spot Paint & Varnish Company, Inc in partnership with the U.S.National Renewable Energy Laboratory. The pure silver self-adhesive film has 94% of specular reflectance.

2.2.15 Solargenix

Solargenix was responsible for EPC at the 1MW Saguaro Power Plant in Arizona, where the collector SGX2 was used (Figure 19). They offer engineering, design, market, manufacture, installation and maintenance of solar thermal systems such as solar water heating and power generation. These include standalone systems, combined with Natural Gas, diesel, wind, biomass and other sources at any desired scale (1MW - 1GW). They offer ground mounting or roof mounting systems (or even roof integration, with the PowerRoofTM product). They contracted personal from LUZ, when it filed for bankruptcy. They have five operating business units, one of them being power generation, which is responsible for the development of solar electric generation systems.

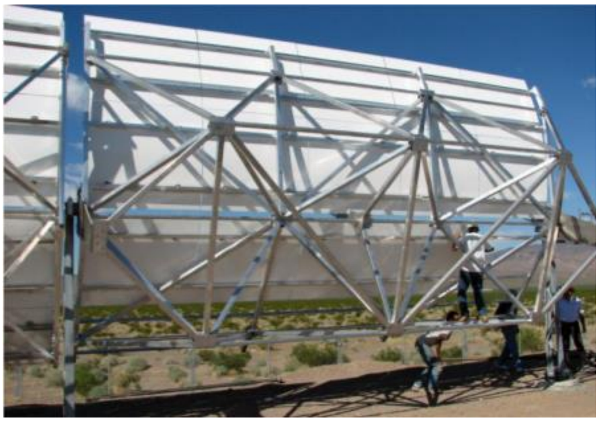


Figure 19 - SGX2 collector from Solargenix [8E].

2.2.16 Torresol O&M

Torresol O&M was created by Torresol Energy, which was created by Sener (60%) and Dhabi-based Masdar (40%). They operate currently three power plants: one tower power plant (Gemasolar) and two parabolic trough power plants (Valle 1/2). Their experiences are about operation and maintenance of parabolic trough power plants and solar tower power plants.

2.2.17 TSK Flagsol

TSK Flagsol has different services and products for solar through power plants. This includes consultancy services, products and components and O&M management. In the past, they provided technology to Spain and Egypt.

2.2.17.1 Products

The products and components offered include steel structures, heat-absorbing elements, mirrors, hydraulic drives, swivel joints and control systems for the whole power plant unit. Products are supplied also via third party suppliers. The company holds patents about storage systems, control details and technical details from the collector and heat transfer medium. The company also develops and distributes vehicles for mirror cleaning.

Collectors: Two collectors were developed and manufactured by this company, Skal-ET (Euro Trough) and HelioTrough. For the past power plants, Skal-ET collector was used, but now the new developed HelioTrough is available. Their Skal-ET collector showed an improvement of +10% more efficiency, less weight and fewer deformations than previous models. The research project was concluded in 2003, and the model was implemented in different commercial power plants such as the Andasol and Astexol II plants in Spain. The new model HelioTrough (Figure 20) collector followed the Skal-ET with the purpose of achieving lower cost keeping good efficiency. It was developed together with partners such as Schlaich Bergermann und Partner, the Fraunhofer Institute for Material Flow and Logistics and the German Aerospace Center (DLR). It was co-funded by the BMU, and a demonstration loop (co funded by the US Department of Energy) is in operation at a commercial power plant in US since 2009. With its 5052 m2, it provides about 3.5 MWt. According to TSK Flagsol, is available as a product or licensed to third parties for construction [2/3F].

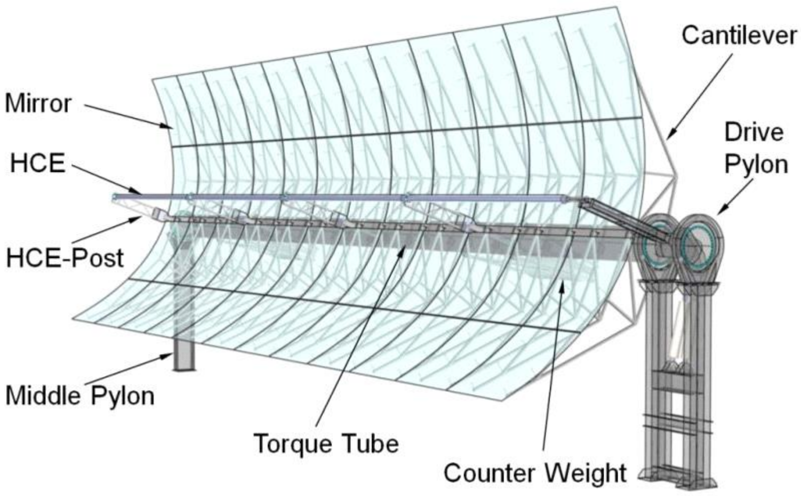


Figure 20 - HelioTrough collector [3F].

Thermal energy storage: Relatively to molten salt technology, the company gained experience in the Andasol projects.

Heat transfer fluid system: About the heat transfer oil which operates up to 400ºC, the company designs, supplies and builds HTF systems including piping, preparation and compensation system.

Control system: Experience from this company in past power plants are the base of developed control system components, such as the Distributed Control System (DCS), Field Supervisory Control (FSC) and Local Control (LOC). These include: the solar field control - the control of one individual solar field collector, including the power supply to drive motors, temperature and position sensor signal processing, data exchanges and alarm output; the improvement of the field operation, and an interface operator versus solar field providing data about the current state.

2.2.17.2 Services

The services from this company go through the main phases of a solar thermal power plant. They offer consultation, feasibility studies, project development, capital participation, granting licenses and engineering for collectors, EPC and O&M.

Engineering, Procurement and Construction: During the engineering phase, technical and commercial specifications are defined. Basic and detail engineering is offered by the company, for a fully operable solar thermal power plant (power block, solar field, HTF system, thermal storage): process, mechanical, civil and electrical engineering, plus instrumentation, control, plant and piping design. During the procurement phase, through the close contact to key suppliers, the best market offers are selected and transportation of the equipment is managed.

O&M: TSK Flagsol offer a O&M service for entire parabolic trough power plants with a smooth transmission from the construction phase to the O&M phase. It includes inspections, preventive maintenance, repair and general overhaul.

2.2.18 WaterFX

WaterFX is a private company which recently started with solar desalination plants, using parabolic trough technology. Together with SkyFuel, they operate a 480 kW demonstration plant in California. Currently WaterFX is developing a larger plant to be running by the end of 2014. Its desalination plant, Aqua4, is a modular solar parabolic trough plant which is able to treat and desalinate any kind of water source: wastewater, drainage water, runoff, saline groundwater and industrial process water. The remaining brine is a byproduct with valuable materials for sale. The plant is automatized, so operation costs are low. Dirty drainage water - with selenium and other toxic minerals is turned into pure H_2O. Due to the absence of fuel cost, WaterFX can sell water at half the price of fossil powered desalination.

At the desalination plant, heat is collected by the solar trough collector, using oil as heat transfer fluid. This heat generates steam through a multi-effect evaporator, which is used to condense and recover fresh water. To improve plant output, a heat pump recovers waste steam, a thermal storage system makes possible a 24h operation. One module of the Aqua4 plant consists on a 400 kW trough collector. Each module produces 262 thousand cubic meters per day, which is 408 L/m²/day.

2.3 Existing power plants

As there are daily new news about parabolic trough power plants, it is important to notice here that the status of existing power plants presented below represents the status for May/June 2014.

2.3.1 Power plants in operation

As can be seen in the Table 3 and Table 4, Spain and the USA are both the markets which had most success in the past. In Spain, all power plants have the same rated power of 50 MWe, except Borges which has 22.5 MW. In the rest of the world, the rated power is variable, but usually in the scale smaller than 100 MW. The size of the power plants is rising with time, reflecting the better economic feasibility for large scale generation.

Table 3 - Operating parabolic trough power plants in Spain.

Spain			MWe
Arenales PS	Helios 1/2	Solacor 1/2	50
La Africana	Andasol 1/2/3	Solnova 1/3/4	
ASTE – 1A/1B	Consol Orellana	Soluz Guzman	
Astexol-2	Palma del Rio I/II	Majadas	
Enerstar Villena	Morón	Termosol 1/2	
Casablanca	Olivenza I	Valle 1/2	
La Dehesa	Puertollano Ibersol	Solaben 6	
La Florida	La Risca	Solaben I/II/III	
Extresol 1/2/3	Lebrija 1		
HelioEnergy 1/2	Manchasol 1/2		
	Borges		22.5

Table 4 - Operating parabolic trough power plants in the whole world, except Spain.

Others		MWe
USA	SEGS I/II/III/IV/V/VI/VII/VIII/IX	14/6x33/89/89
	Martin Next Generation Solar Energy Center	75
	Nevada Solar One	64
	Holaniku at Keyhole Point	2
	Genesis Solar 2	125
	Saguaro Power Plant	1.16
	Solana	280
Italy	ASE Demo Plant	2
	Archimede	5
Morocco	Ain-Beni-Mathar ISCC	20
Algeria	Hassi-R'mel	25
Thailand	Kanchanaburi	5
Egypt	Kuraymat ISCC	20
India	Godawari	50
	Indian Institute of Technology CSP Project	3
Oman	Petroleum Development Oman CSP EOR Project	7

Chile	Minera el Tesoro	10
UAE	Shams 1	100

2.3.1.1 Spain

As Spain has good conditions for CSP, including flat land and abundant solar resource, in 2002 the Spanish Government decided to start a feed-in-tariff for solar thermal power, the first in Europe (Table 5).

Table 5 - Policy in Spain until 2013.

	First 25 years	Afterwards	Description
Feed-in-tariff, September 2002	pool price + 12 €cents/kWh		100 kW - 50 MW plants
Royal Decree 436/2004	300 % of rp	240% of rp	sell to a distributor
	market price + 250 % of rp	market price + 200% of rp	sell to free market, +10% incentive
RoyalDecree 661/2007	27 €cents/kWh	21.5 €cents/kWh	Tariff increased yearly with the CPI (Consumer price index)-1%. 12-15% backup allowed.
	market price + 25.4 €cent/kWh	market price + 20.3 €cents/kWh	
January 2012 - Canceling program from 2007	Not available for new applicants		
Measures 2012 - 2013	+ 7% tax to income for power producer, canceling second option premium market price and other measures.		

But it was not enough to cover cost and risk. New regulations came in 2004, and were redefined in May 2007 with the Royal Decree 661. At the end of 2009, a total of 51 power plants were registered to join the subsidy in the period 2010-2013. At the moment the installed and operating capacity is over 2 GW. In the Figure 21 and Figure 22 and it can be observed when and where these power plants entered into operation. Most power plants entered into operation clearly in the period where the Government offered attractive policies. In the beginning of 2012, the program closed for new applicants. Than until 2013, the Government changed policy including new taxes, decreasing income depending on the use of natural gas (decrease in the tariff proportional to natural gas used, and additional tax), canceling the correction by CPI and the second option from RoyalDecree661/2007. For now, no new CSP is expected for Spain due to the moratorium decreed by the government [2G].

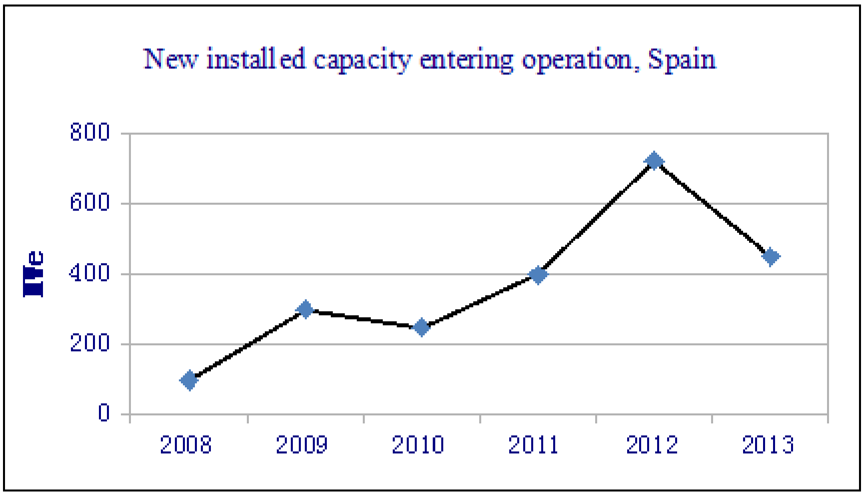


Figure 21 - New installed capacity of parabolic trough power plants in Spain based on the created database.

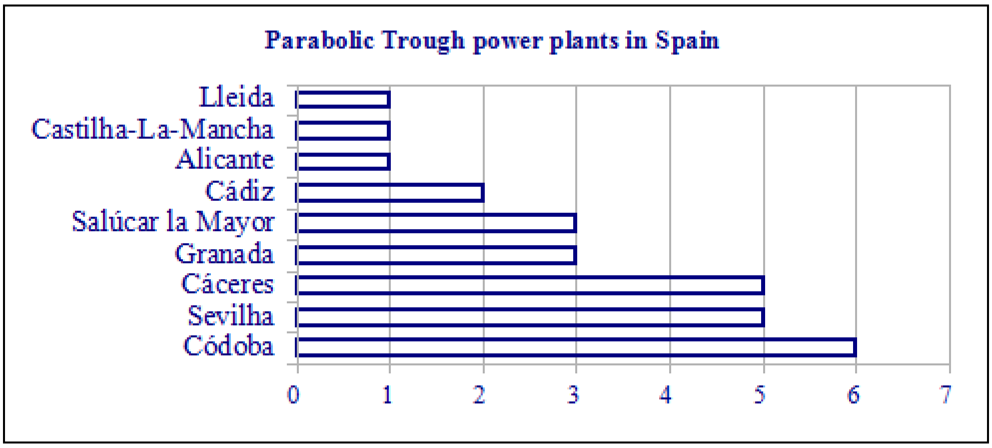
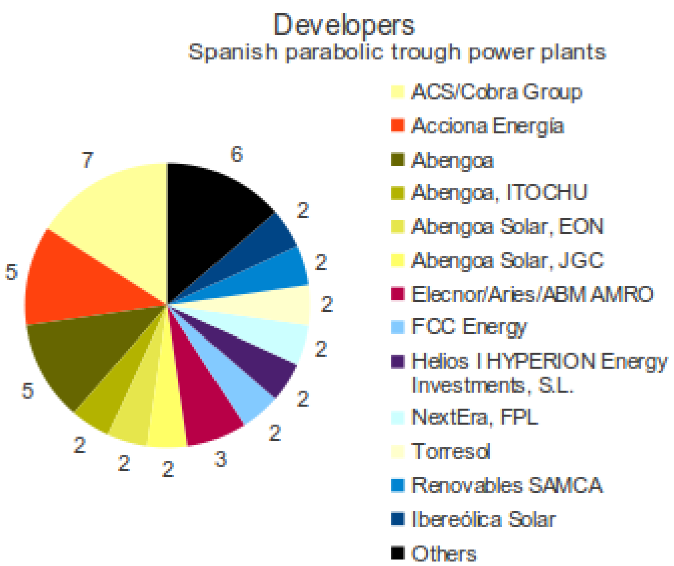


Figure 22 - Location of operating parabolic trough power plants in Spain based on the created database.

The average investment cost of operating power plants was 5.9 € per W of capacity installed and the average land area required was 3.5 m²/kWe. Nearly half of the existing power plants have storage systems. They opted for two tank indirect molten salt with 28.5-30 thousand ton of a mixture of 60% sodium nitrate and 40% potassium nitrate which allows the 50 MW power plants to operate at rated power during 7-9 hours of nighttime or cloudy weather. All power plants use wet cooling systems. As allowed by the Spanish policy, most power plants have a 12% backup system with a HTF boiler. Borges Termosolar is the first commercial hybrid parabolic trough power plant using Biomass as second heat source.

The EPC companies which build up these trough power plants were mainly Abener/Teyma, Acciona Energía, Cobra, Sener, Abantia, SerIDOM and others. As can be seen in the Figure 23 (left side), Abengoa and Cobra Group were the main developers, followed by Acciona Energía and other developer companies. The main operation and maintenance companies were Cobra O&M, Abengoa Solar, Acciona Energía, Torresol and others. Companies such as Cobra Group, Ibereólica Solar, Acciona Energía, Abengoa Solar and Torresol also are the owners of several parabolic trough power plants.



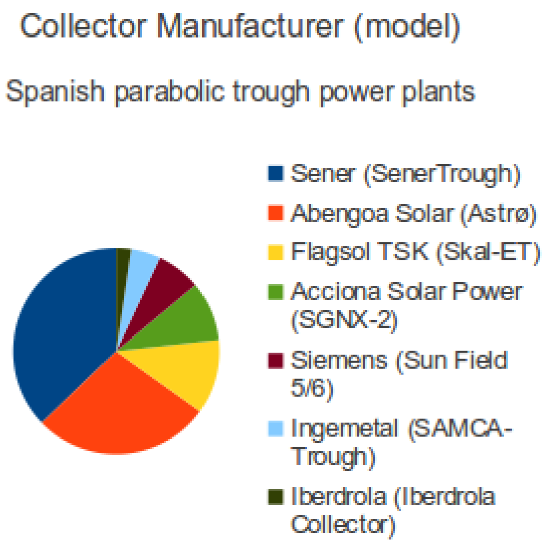


Figure 23 - Developer of Spanish parabolic trough power plants (left side) and collector manufacturers (right side) based on the created database.

The receiver model used was supplied mainly by the company Schott. This company manufactured more than one million PTR®70 receivers until the end of 2013 [1H]. Also Siemens offered receiver models such as UVAC 2008 and UVAC 2010, but at the end of 2012 Siemens decided to exit the solar business. For the mirrors, two major companies are on the market, Flaberg and Rioglass Solar SA. The heat transfer fluid used was thermal oil, a mixture of Diphenyl/Biphenyl Oxide provided by the company DowthermTM. For the turbine unit, Siemens and MAN Turbo were two reference suppliers. For the solar collector, the two major manufacturers are Sener, Abengoa Solar and Flagsol TSK, as can be seen in the Figure 23 (right side) .

2.3.1.2 USA

From the list of operating power plants (Table 4), the country which has currently most operating parabolic trough power plants after Spain is USA, with a total capacity over 1 GW.

The start of parabolic trough is related to the 1970s oil-crises, where the USA started a tax and investment incentive on alternative energy, covering nearly 40% of the costs [3G]. As a result, the first power plant which was SEGS I, started its operation in 1984. This 14 MW power plant was followed by eight SEGS plants, which had 33 MW each, except the last two large plants with 89 MW each, entering into operation in the period of 1985 - 1990. They were all installed in California, as “Qualifying Facility Independent Power Producers”, with special Standard Offer 2 as the tariff agreement to Southern California Edison. Luz, which was an Israeli start-up, developed these power plants, NextEra and Cogentrix are the owners and operators. They include natural gas backup but no storage system. The solar collector was provided by Luz (Ls 1 - 3), and the receiver was provided by Solel, inside which the heat transfer fluid Therminol flows.

Between 1985 and 1989, as a result of large scale production and development, the cost decreased by 50% - starting from US$0.30/kWh to US$0.14/kWh [3G]. As can be seen in the Figure 24, after 1990 there was a period of 16 years without any new parabolic trough power plants. As the oil prices decreased again, the incentive was dropped to 1/4. As a result, the solar collector manufacturer and developer of parabolic trough plants Luz went under in 1991. But Florida Power & Light (FPL) kept the plants running with great success, showing that the technology is ready for the large scale market.

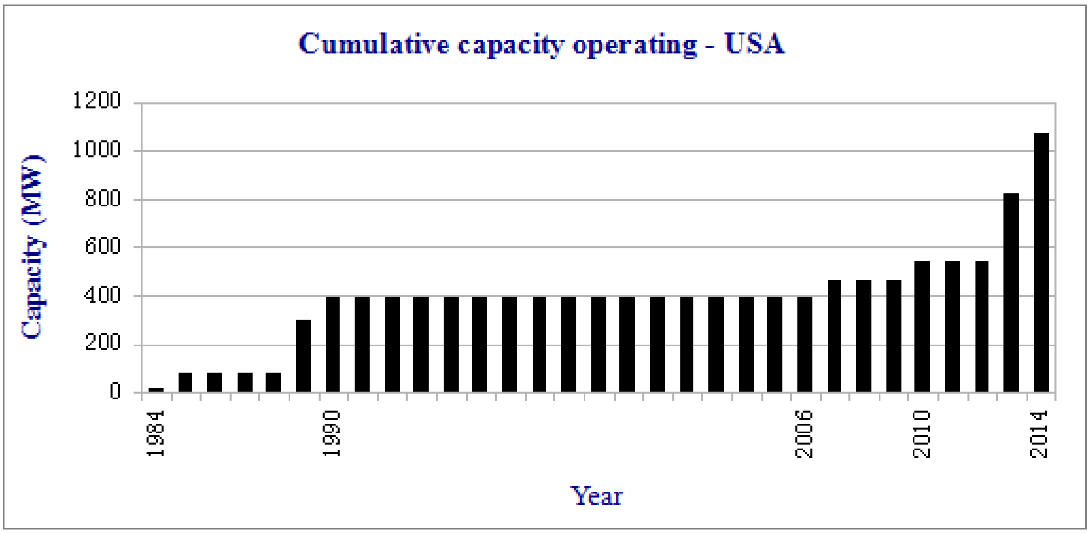


Figure 24 - Cumulative capacity operating in USA based on the created database.

The ITC (Investment Tax Credit) started in 2006 and supports renewable energy in the residential and commercial properties. It is an incentive which provide 30% of the expenditures for solar systems, including CSP. Several times the period was extended, and at the end it will be valid until 2016. These incentives gave support for new power plants.

In 2006, two small power plants, one in Hawaii (0.5) and one in Arizona (1.16 MW) entered into operation. In 2007 a 75 MW power plant entered into operation in Nevada, the Nevada Solar One power plant, followed in 2010 by Martin Next Generation Solar Energy Center, a 75 MW power plant in Florida. Finally, two large power plants entered into operation in 2013 and 2014, the 280 MW Solana plant (Arizona) and the 250 MW Genesis Solar Energy Project (California). The great improvement of the Genesis Solar Energy Project is the use of a dry air cooling condenser, which saves huge amounts of water.

Important developer and/or EPC companies were Abener/Teyma, Lauren Engineering, Acciona Solar Power, NextEra Energy Sources, LLC, Florida Power &Light Co. and Genesis Solar, LLC. Comparing to Spain, the ratio of power plants which have storage system is quite smaller, less than one third use molten salts. Most collectors used were manufactured by Luz, Abengoa and Sener (Figure 25).

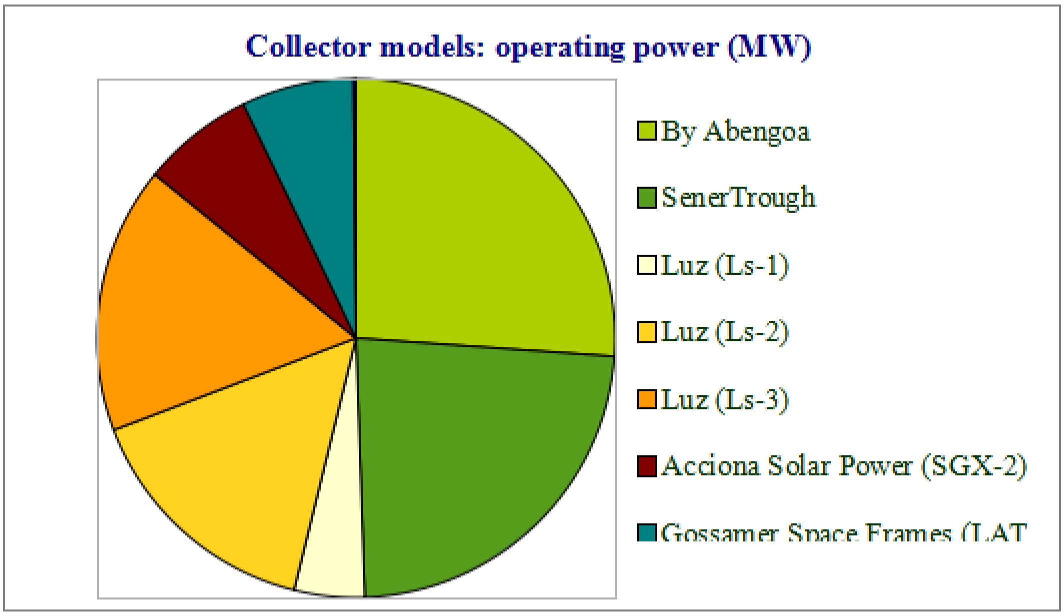


Figure 25 - Collector manufactures of operating parabolic trough plants in USA based on the created database.

2.3.1.3 Other countries

Beside the USA and Spain, several power plants were installed all around the world (Table 4). One big 100 MW plant is operating in the UAE since 2013, with all main components and services provided by Abengoa Solar. It works with dry cooling system and has natural gas backup. In India Godawari is operating since the same year, providing 50 MW, developed and owned by Godawari Green Energy Limited, the EPC provided by Lauren-Jyoti. Three more large-scale power plants are operating since more than three years, in Morocco (20 W), Algeria (25MW) and Egypt (20 MW). All of them use wet cooling systems except Hissi-R'mel in Algeria, which uses dry air condensers. Beside these large-scale power plants, there are several power plants <5 MW in Italy, Thailand and India. There are also some small thermal power plants, which use thermal energy directly (as for oil extraction and industrial processes). An example is the Petroleum Development Oman CSP EOR Project in Oman engineered by GlassPoint, which drives a solar enhanced oil recovery system.

The main company which was responsible for development, EPC, O&M services is Abengoa Solar (Abener). For the heat collector, the model PTR70 from Schott was mostly used, as well as mirrors from Rioglass and Flaberg (RP3), the solar collector Astrø (but also SKAL-ET from Flagsol), and finally the HTF Therminol-VP-1 from Solutia and Dowtherm A from DowChemical. Beside the power plant in Algeria and UAE, all other work with wet cooling system.

2.3.2 New power plants

As the Spanish government changed its policy, the growing CSP industry in Spain slowed down. But, as it has been proven widely that parabolic trough technology is able to provide stable electricity to the grid, the rest of the World starts to show great interest in this technology. There are new large plants under construction in the USA, South Africa, India and Morocco. Beside, many new power plants are under development and being planned. This includes countries such as China, India, USA, Italy, Chile and even in Africa (Tunisia, Algeria, Egypt, Morocco and South Africa). In order to increase profitability and decrease the LCOE, most power plants aim to have at least 50 MW, up to 500 MW.

3. Project analysis for Morocco

After the last two chapters, it is now clear which technology is in a much more mature state. Parabolic trough power plants are now operating successfully for several years, and the operating capacity reached several GW. Several companies offer EPC services and/or produce and develop specific components such as collectors, tracking systems, and heat transfer fluid or heat collector elements. The support of the USA and Spanish governments for CSP investors can be seen as the main initial incentive which was needed to develop and prove this technology in real conditions at a large scale. On the other hand, even if there were huge plans of large scale parabolic dish power plants, most of these did not reach the complete construction and operating phase. Therefore this technology still is not well proven in a long term and large scale, and there are no companies which sale commercial products. Still there are companies which are investing in investigation projects for Stirling dishes and others different than Stirling. Maybe in short term good results will be proved, but it is not guaranteed.

Therefore, and in order to better understand if the government supports were enough to take the parabolic trough technology in an advanced state, the following economic simulations were developed for Morocco.

Morocco is located in the Sunbelt region, creating optimum conditions for solar power generation. The state owned Office National de l' Electricite (ONE) is responsible for electric power generation and operation of plants. But as a result of the power scarcity, the power sector was liberalized. In 2012, the total generation from renewable sources was 9.6 %. Morocco is extremely dependent on foreign energy supply, so 97% of the total energy supply comes from outside, mainly coal and oil. Combining the favorable solar conditions (Figure 26) and the dependence on foreign sources (including electricity from Spain, through the submarine connection at the Strait of Gibraltar), Morocco decided to choose solar power as the path for the future. The national energy strategy set a target of 42% of its total energy production coming from renewable energy by 2020. The Solar Program is also included in this strategy, starting with the project Ouarzazate for generating 500 MW. This project plans the construction of three power plants, one of them power tower and the other two parabolic trough. At 2020, this program expects a total constructed capacity of 2GW, which will be 14% of the power installed by 2020. The Solar Program is being leaded by MASEN (Moroccan Agency for Solar Energy), which was created in 2010. The total investment estimated is 9 billion USD.

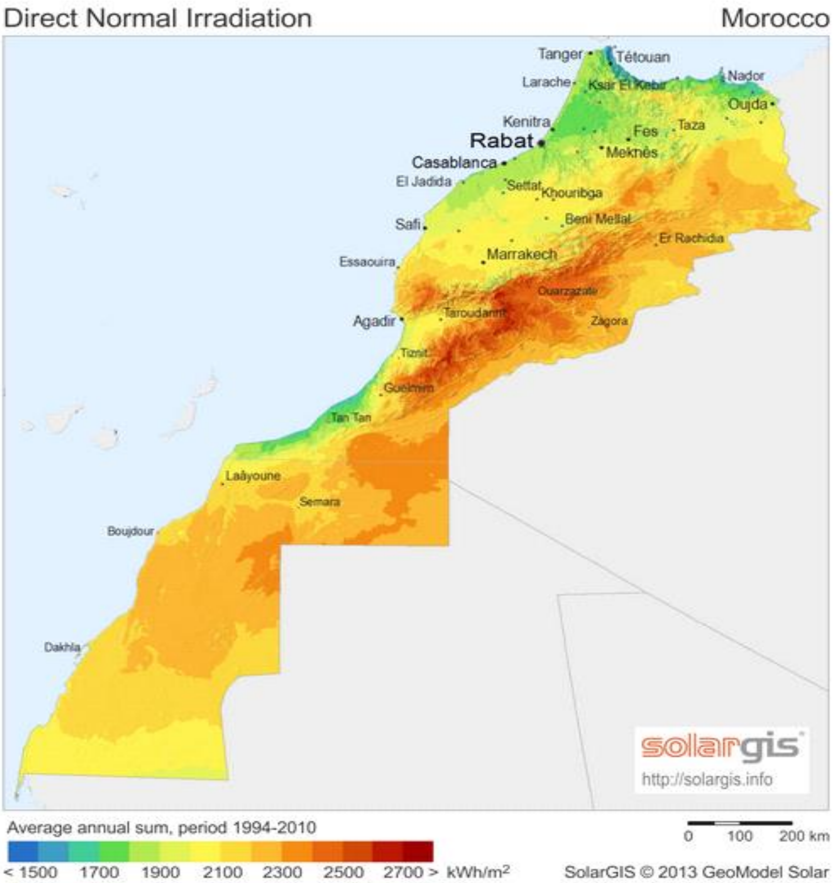


Figure 26 - Average annual solar resource in Morocco (kWh/m^2). Reference is shown at the figure.

3.1 CSP power plants in Morocco

In Morocco, beside Aïn Beni Mathar ISCC which is currently in operation, more five power plants are expected to operate in the near future. Two are under construction, and more 3 are under development.

The first CSP power plant entering into operation in Morocco was Aïn Beni Mathar ISCC in May, 2010. This hybrid parabolic trough system combines a steam Rankine cycle with 20 MW of solar generation and 450 MW of conventional generation (natural gas). It uses the concentrator Astrø and the cooling system is dry. The total cost was 400 million €, and financing was provided by the African Development Bank, Office Nationale de l'Electricite, Global Environment Facility and Instituto de Credito Official. In the following **table** are described the technology suppliers.

Table 6 - Companies involved in the development/ construction of Aïn Beni Mathar ISCC [4].

Project developer	Abener
EPC	Abener
O&M	Abengoa Solar, Office Nationale de l'Electricite
Key components suppliers	Fichter Solar Telvent Therminol
Basic and Detail engineering	IDOM
Valves	BValve
Valves, turbine bypass	Schubert & Salzer BValve

Consultancy/conceptual design	Fichter Solar
Actuators	Drehmo
HTF	Solutia Terminol
Valves	Leser

The power plants which are under construction are Airlight Energy Ait Baha CSP and Ouarzazatake (see Table 7). Both will use parabolic trough concentrators. The first one is for demonstration purposes, and will provide 3 MW of solar energy to an existing 12 MW Organic Rankine Cycle unit. Twelve hours of storage are planned using pebble stone. The company Airlight Energy is the main technology provider and developer, but O&M will be from the responsibility of Cimar Italcementi Group. It is expected to start operation in 2014. The second one, Oarzazatake will be for commercial electricity production, with 160 MW of solar energy. In 2013 the construction began, and it is expected to enter into operation in 2015. The total cost is estimated of 1042 million Euro. Three hours of storage are planned with molten salt technology.

Table 7 - CSP power plants in Morocco [4].

	Airlight Energy Ait Baha CSP	CNIM eCare Solar Thermal Project	Ouarzazate	Ouarzazate 2	Ouarzazate 3
Status	Under Construction	Development	Construction	Development	Development
Power (MW)	3 solar for 12 MW ORC	1	160	100	200
Technology	Trough	Fresnel	Parabolic trough	Power tower	Parabolic trough
Owner	Cimar Italcementi Group	CNIM	ACWA Aries MASEN TSK	MASEN	MASEN
Location	Ait Baha	Undefined	Ouarzazate	Ouarzazate	Ouarzazate
Solar collector	Airlight Energy	CNIM	SENERTrough		
HTF	Air	Water			
HTF T_{out} (ºC)	650	280			
Cooling		Dry air cooler			
Project developer	Airlight Energy	CNIM	ACWA Aries TSK		
O&M	Cimar Italcementi Group		NOMAC (ACWA)		
Tariff		French Renewable Energy Program	0.136 €/kWh for 25 years		

A 1MW Fresnel demonstration power plant is planned to be developed by CNIM. A storage system based on steam drum for 2h is also included, and the cooling system will be a dry air cooler. There will be four solar concentrator arrays providing heat to an organic Rankine cycle unit, using water as heat transfer fluid. Finally, two additional commercial power plants are under development for Ourzazate, including one parabolic trough power plant and one power tower plant.

3.2 Methodology

To develop an economic feasibility analysis for a parabolic trough power plant in Morocco, there are several aspects and variables to be considered.

The first aspect is the location of the power plant. The location will define not only the solar resource availability, as well as other environmental variables such as the wind speed, ambient temperature, the relative humidity and sea level pressure, which have an impact on the productivity of the power plant. For this study, the eight more populated cities were chosen, as well as Ouarzazate where the Solar Program projects are developed, for comparison (see Figure 27). Clearly Casablanca is the most populated town. But actually Rabat, Salé and Kenitra are very close to each other, creating another consumer area with nearly two million inhabitants. On the other hand Ouarzazate, where the solar resource seems to be very high (Figure 26), there are just 149 thousand inhabitants.

To choose populated cities for this kind of analysis means that the electricity production is near the consumer (which decreases transportation costs and losses) and usually meteorological data is available for longer periods. The availability of enough space could be a challenge, but the idea is that these power plants are at the surroundings just as close as possible to the town, so that the meteorological data is still valid.

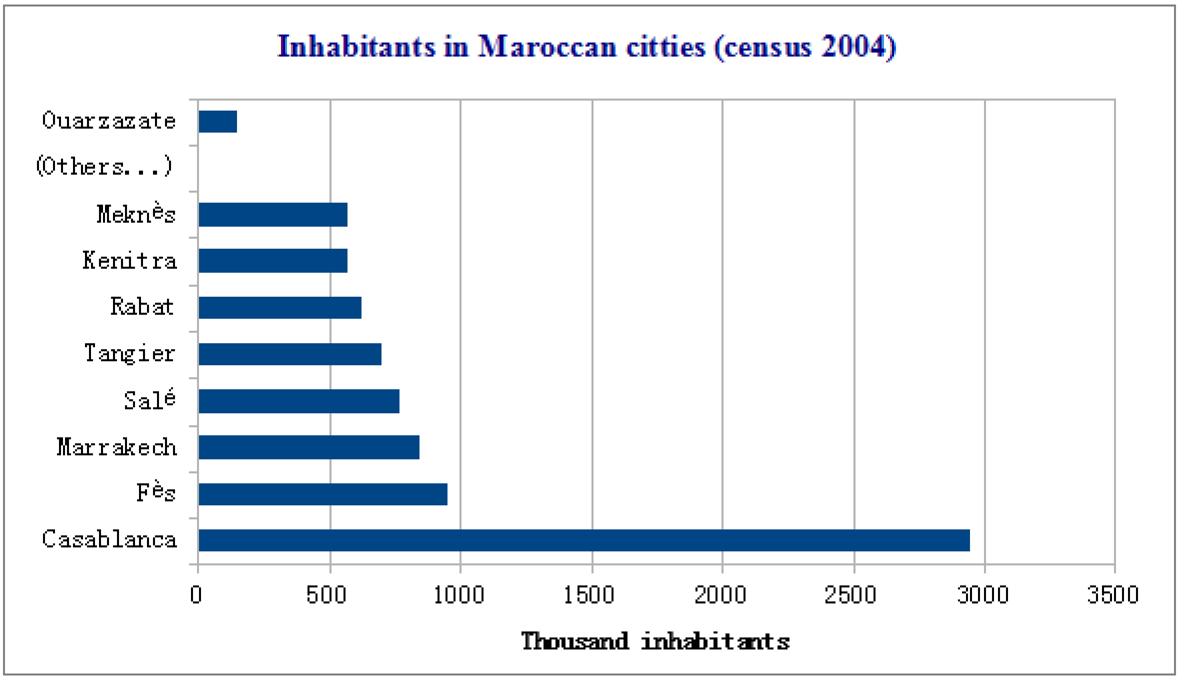


Figure 27 - Inhabitants in the eight largest Maroccan citties as well as Ouarzazate (data from the census 2004).

For each location, the solar resource and meteorological data was compiled. The solar data was taken from the PVGIS database (re.jrc.ec.europa.eu/pvgis/apps4/pvest.php?map=africa) which provides data for every 15 min for any location in Africa during a typical year. The other meteorological data were taken from the WeatherUnderground database (http://www.wunderground.com/). Measured hourly data is provided for every year since the start of each meteorological station. Rabat, Kenitra and Salé are very close to each other and so the same meteorological and solar data is used, from the station Rabat-Sale. All other meteorological data were taken from meteorological stations in each city airport (see the station codes in the Table 8).

Table 8 - Meteorological stations from the Airports of each location.

Place	**Region**	**Meteorological station**
Casablanca	Grand Casablanca	GMMC
Fès	Fès-Boulemane	GMFF
Marrakech	Marrakesh-Tensift-El Haouz	GMMX
Salé	Rabat-Salé-Zemmour-Zaer	GMME
Tangier	Tanger-Tetouan	GMTT
Rabat	Rabat-Salé-Zemmour-Zaer	like Salé
Kenitra	Gharb-Chrarda-Béni Hssen	like Salé
Meknès	Meknès-Tafilalet	GMFM

Ouarzazate	Souss-Massa-Drâa	GMMZ

To compile the data and create a table for hourly values for one typical meteorological year, Software tools from Ubuntu such as the LibreOffice Calc and GNU Octave 3.2.4 were used. For the solar data, the hourly data was calculated by linear interpolation of the 15 min values. For the other meteorological data, a mean of the available years was used. For Ouarzazate data is available since 2012 and for Meknes and Casablanca data is available since 2011 which is not good enough, but for all other stations data is available since the year 2005. With these data a TMY3 file was created for each location representing a typical meteorological year. This file includes the global irradiance on a horizontal surface, the direct normal irradiance, the diffuse irradiance on a horizontal surface, the wind speed, the ambient temperature, the relative humidity and the sea level pressure.

For calculating the yearly electricity output, the program SAM version 2014.1.14 (System Advisor Model) was used. This program is provided by the U.S. Department of Energy and National Renewable Energy Laboratory's (NREL). It provides financial and performance analysis for different renewable energy systems such as wind turbines, PV systems, conventional power plants, solar water heating, biomass, geothermal and concentrating technologies. These include technologies such as the power tower, linear trough and linear Fresnel and even the parabolic dish.

In SAM, the first step is to define the location of the power plant, uploading a TMY3 weather file corresponding to the local conditions. But to calculate the yearly electricity production, the program requires not only the TMY3 weather file mentioned before but also technical properties of the power plant. So before using the SAM, the next step after creating the weather file was to size the power plant and to choose the technology.

3.2.1 System sizing

There are some parameters which should be fixed when sizing a power plant. For this case, they are the rated capacity, the storage capacity and solar multiple (which represents the solar field area as a multiple of the power blocks rated capacity). For the rated capacity, 50 MW were used, as it is the dominant size for existing power plants especially in Spain, representing the size with more past experience. For the solar multiple and storage capacity, two combinations were used, which minimize the total cost for two different CSP grid incorporation targets.

When comparing different technologies of electricity generation, usually the LCOE value is used as the comparison reference. Comparing exclusively the LCOE, CSP is not competitive with wind and PV technologies. But for a high incorporation of fluctuating renewable energy into a grid system, the dispatchability rises as an important value and CSP shows great advantages. According to Brand et al, 2012 ([2H]), there are two aspects which LCOE does not take into account. One is the "time of delivery value", which represents the cost savings when a certain power plant provides power at peak load time avoiding the need of an additional peak load plant. For CSP, this happens through thermal storage. The second aspect is related to the "ability to provide firm capacity to the power system", which for CSP represents the ability to run with conventional fuel when the solar resource is low, enabling a 365 day/year power supply. In Morocco the state is still the owner and operator of power plants, who makes decisions about new investments and who is interested in holding the total system cost low. Therefore when it comes to project analysis it makes more sense to include these two aspects rather than analyzing just the LCOE value. Brand et al. analyzed the effect of high incorporation of CSP in the conventional electricity systems in Morocco and Algeria and how it affects system optimization. First of all, storage-based CSP plants are more economically feasible than without storage, for both countries. Depending on the CSP incorporation into the national grid, different optimum combinations of solar multiple and storage capacity were found. Increasing the solar multiple (SM>1) results in a solar field that operates at its designed point for more hours of the year and generates more electricity. The results for Morocco are presented in Table 9, and will be used for the SAM simulations in this study.

Table 9 - Cost-minimizing combinations of SM and storage capacity for the integration of CSP plants into the moroccan grid until 2025 [2H].

	Morocco
5% CSP incorporation target	SM 1.75/ 4 h
20% CSP incorporation target	SM 2/ 6 h

For projects that deviate from these values, the total system cost increases rapidly [2H]. For too large storage systems, less energy is dumped but additional energy production cannot compensate costs. For too low storage systems, the electricity grid has to compensate the variable solar power plants. Which in the case of Morocco is quite difficult, as the grid is dominated by non-flexible coal power plants, which should not be switched on or off frequently.

3.2.2 Technical details

The market analysis shows which technologies and products had been more common in past power plants, and those were chosen for the study. SAM includes a library about the properties of many products which are in the market currently, including the ones which were considered to be more common in past power plants.

First, the turbine in the power cycle must be chosen. Operating power plants use not only MAN Turbo turbines, but specially the Siemens model SST-700 which is widely used all over the world, including most power plants in Spain and in other countries like India, Algeria and Egypt. Its properties are available at the SAM library. Accounting for an estimated gross to net conversion factor of 0.9 which represents the parasitic losses, the design gross output of a 50 MW plant is 55 MWe. Therefore SST-700 turbine for 400ºC with 55MWe gross output was chosen.

Than the solar field components must be chosen, including the heat collector element and the solar collector assembly. In Spain, the two major collector manufacturers are Sener (SenerTrough), Abengoa Solar (Astrø) and Flagsol TSK (Skal-ET). In the USA, the large Genesis Solar project used SenerTrough and in Morocco, the existing plant uses Astrø. But as the model ET150 is available in the SAM program and was actually used in many plants in Spain, Egypt and India, this product was chosen for this study. Collectors are oriented in a North-South axis. For the heat collector element, the model PTR®70 was chosen. More than one million units were produced by the Scott until the end of 2013. The corresponding data is also available on the SAM library.

For the storage system, the storage capacity was defined as described in the last section. The storage fluid type was Therminol VP-1 has been widely used not only in the USA, but also in many other countries over the World including Egypt, India, Spain and Morocco. It is a thermal oil, a mixture of Diphenyl/Biphenyl Oxide provided by the company Dowtherm^{TM}. The thermal storage system works with the salt Solar Salt, which is also widely used in other studies as a reference product, and it is as well available at the SAM library. For the dispatch rules, the “Generic Summer Peak” schedule was chosen. It respects that especially in summertime the electric grid needs more support during the period 12 pm to 5 pm, when air conditioning consumes a lot of electricity.

Table 10 - Assumed technology for the study.

Component	**Model**
Turbine	Siemens SST700 for 400ºC
Solar collector assembly	ET150
Heat collector element	Schott PTR®70
Storage fluid type	Solar Salt
Heat transfer fluid	Therminol VP-1

3.3 Data and assumptions

In the economic analysis, three values were calculated: the net present value (NPV), the internal rate of return (IRR) and the levelized cost of electricity (LCOE). The assumptions are listed in Table 11 and the equations used are described below. Note that the convention used for these equations is that a variable representing a monetary value which is a loss for the investor - a negative cash flow like O&M costs, taxes and the investment - should be negative when introduced in the formulas.

Table 11 - Assumptions for the economic analysis.

Construction time	**2 years**
Lifetime	**24 years**
Interest rate	**3.07% (2015), 3.30% (2020) and 3.76% (2030)**
Risk of country	**2%**
Inflation	**2.5% (2015 - 2019), 3.75% (2020), 4.00% (2030)**
Working capital	**5% of the initial investment**
Residual value	**10% of the initial investment**
System degradation	**0.5%/y**
Tax	**10%**
Tariff	**0.13 €/kWh**
Tariff variation	**Inflation/2**
EPC	22 M€
O&M costs	0.12 €/W
Sun tracking	11.0 M€
Collector	58.0 M€
Heat transfer fluid 4h/6h storage	2.0 / 2.5 M€
Molten Salt Inventory 4h/6h storage	2.4 / 2.9 M€
Storage tank 4h/6h storage	0.9 / 1.0 M€
Storage tank foundation + insulation 4h/6h storage	0.15 + 0.01 / 0.17 + 0.01 M€
Turbine	2.6 M€

The levelized cost of electricity reflects the cost per kWh produced. It is very useful for comparing two different projects with different costs, different technologies or different resources available for production. Equation (1) describes how the LCOE was calculated. The sum of all costs during the whole lifetime of the system are divided by the produced electricity during this period, both values are calculated for the present.

$$LCOE = \frac{\sum_{i=0}^{25} \frac{1}{(1+a_i)^i} \times \left[I_i + Buffer_i + RV_i + OMI_i \right]}{E_{1st\_y} \sum_{i=0}^{25} \frac{1}{(1+a_i)^i} \times (1-dgr)^{i-1}} \tag{1}$$

The power plant is to be constructed in the year 2015 and 2016, and is to operate during a total of 24 years, which means that in 2040 the plant will have reached the end of its life. In the equation (1), the variable ‘a’ represents the actualization rate, which is different each year and results by the combination of the risk of country, the inflation and the interest rate, calculated like described in the equation (2).

$$a_i = (1+\text{int}_i) \times (1+risk) \times (1+\text{inf}_i) - 1 \tag{2}$$

For the interest rate, a forecast for the years 2015, 2020 and 2030 was used, taken from the source [5H]. With these three values, the whole period 2015 - 2030 was calculated using linear interpolation. For the risk of country, 2% was assumed since Morocco is a relatively stable country from the political point of view. For the inflation, one forecast referring to the period 2015-2019 from the IMF [4H] was used. For the period 2020 - 2030, an interpolation with the forecasts for 2020 and 2030 from [5H] was used. For the years after this period, the average of the last 10 years was used. Past inflation values for Morocco are relatively stable when comparing many other neighboring countries.

The costs in equation (1) includes I, the initial investment. It is the sum of the EPC costs and components. The components included are listed in Table 11: the collectors, the sun tracking system, the heat transfer fluid, molten salt inventory, the storage tank with foundation and insulation, and finally the turbine. EPC costs and collector prices were taken from [8E], which refers to a 50 MW plant using the ET150 collectors. All other components were taken from [3H], which exclude heat exchangers and salt pumps.

The costs include also more 5% of the investment, the so-called working capital which takes into account the deviation between the operation and maintenance costs and the earnings. The third cost parameter is actually not a cost but a revenue, which is coupled to the material which can be sold at the end of the power plants lifetime - the residual value. It is considered to be 10% of the total initial investment. Finally, the fourth cost parameter (OM in equation (1)) relates to the operation and maintenance costs and insurance costs. For the first year, it is considered to be 0.12 €/W (from [8E]), afterwards it increases with the inflation.

About the denominator in equation (1), which is the total produced electricity during powerplant’s lifetime, it is a result of the electricity produced in the first year (calculated with the SAM program) and the system degradation. The system degradation rate is considered to be 0.5% per year.

About the IRR: it represents what the investor can gain with the project. The value should be greater than the interest rate so that the project shows advantages for the investor. In terms of mathematics, it is the interest rates for which the NPV is zero. Calculation programs such as Exell or LibreOffice Calc, which were used, calculate the IRR through the global cash flow each year. The NPV also gives a measure of what the investor can gain through the project. It should be greater than zero, otherwise to participate or not in the project is exactly the same situation for the investor. Values below zero mean that the investor could not even get his investment back. It is calculated as described in equation (3), where GCF represents the global cash flow.

$$NPV = \sum_{i=0}^{25} \frac{1}{(1+a)^i} \times GCF_i \qquad (3)$$

The global cash flow is described in equation (4) and represents the investment plus the result after tax. The result before tax is simply the sum of all cash flows for which the tax will be calculated: the electricity sales, the working capital (which is not considered to be recovered at the end of the project), the final residual value and O&M costs. The electricity sales are simply the produced electricity times the tariff. For this study, the tariff of 0.13 €/kWh was used, which corresponds to the tariff of the existing power plant (see Table 7). The tariff was assumed to vary in time with half the inflation rate.

For calculating the tax every year, depreciation has to be taken into account. In Morocco, a tax of 10% is applied to companies based in Morocco [5H]. Tax losses may be carried forward for a period of four years, except the depreciation, which can be carried forward indefinitely.

$$GCF_i = I_i + \left(E_{sales\_i} + Buffer_i + RV_i + OM_i\right) - Tax_i \tag{4}$$

The easiest way to calculate the tax which has to be paid each year, is to construct a table using a calculation program. First, the negative results are listed, excluding depreciation. Than the negative results for the past four years are listed. For the years with positive results, the usable negative results including the last four years are calculated. Than the tax can be applied for these positive values minus the negative past results, but it has to be taken into account which negative results were used before. And, before calculating the tax, the negative depreciation results can also be carried forward to be subtracted to the positive results, decreasing the tax.

3.4 Results

Before analyzing the electricity produced at each site as well as the economic analysis, it is important to distinguish the different locations in terms of ambient conditions. Figure 28 shows the average direct normal irradiation, average ambient temperature and average wind speed for each location. It can be noticed that Tangier has especially a lot of wind, Marrakech is especially warm and the coastal regions (Tangier with 2451 kWh/m^2, Rabat, Sale and Kenitra with 2387 kWh/m^2 and Casablanca with 2296 kWh/m^2) have the highest DNI. For these locations, the DNI is even higher than in Ouarzazate, which is the location of the CSP projects in Morocco and has a DNI of 2249 kWh/m^2. But comparing now these tendencies with the map shown before (Figure 26), there are some interesting differences. At the map, the interior region like Ouarzazate shows higher values than the coastal region. When comparing the implementation of the same solar project for different locations, the solar resource data is crucial. The data from the map was taken from SolarGIS, which provides many solar maps for different countries (for free) and specific irradiation values (for sale). On the other hand, the data used in the simulation (Figure 28) is provided from an open source database - PVGIS, where any error could be corrected at any time. Therefore, this source is considered more reliable and will be used in the simulations. The difference of the two databases can be related to the different simulation models which are used in each case.

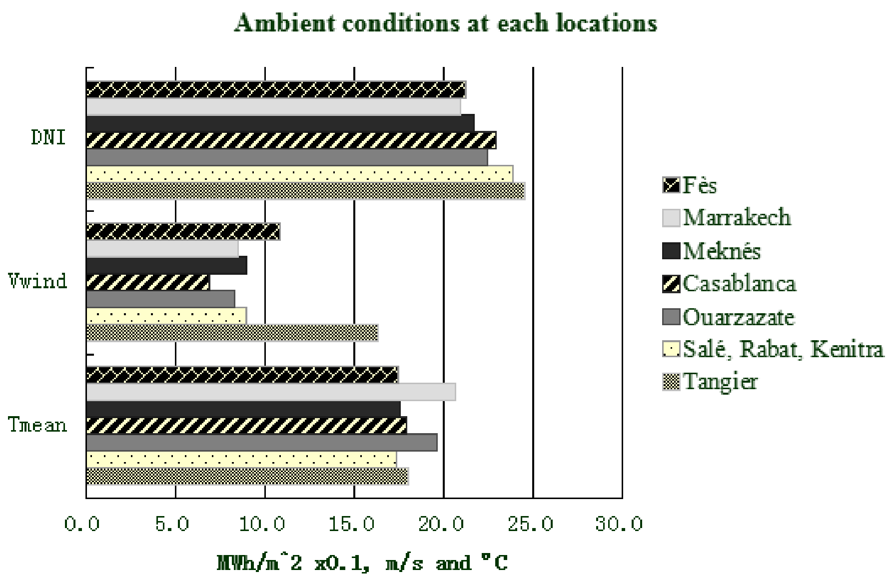


Figure 28 - Average direct normal irradiation, mean ambient temperature and wind speed for each location.

After inserting the ambient and solar dataset and the technical details into the SAM program, the electricity generation was calculated for the two CSP into grid incorporation targets - 5% and 20% (Figure 29). The first thing to be noticed is that for the lower CSP incorporation target conditions, which means less hours of storage and a lower solar multiple coefficient, the electricity generation drops significantly comparing to higher CSP incorporation target conditions. The second thing noticed is that the DNI shown in Figure 28 is the most dominant influence to higher or lower results - obviously a higher solar resource leads to higher electricity production. Except for the case of Ouarzazate and Casablanca. Comparing to Casablanca the DNI for Ouarzazate is slightly lower but the electricity production is higher. Other aspects lead to these deviations, such as the ambient temperature, wind speed and solar resource distribution along the days and months.

In terms of the number of yearly full load hours, the low CSP incorporation target has the lowest value in Fès, 2162 h, and has the largest result for Tangier, 2567 h. For 20% of incorporation target, the locations for the worst and best results are the same, with 2522 h and 2968 h.

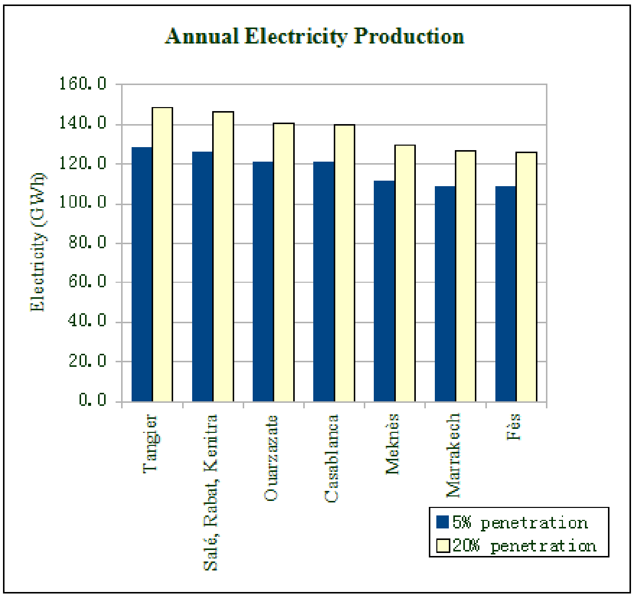


Figure 29 - Annual electricity produced by the power plant for 5% and 20% of CSP integration in the grid.

After inserting the SAM results for electricity generation in the developed economic analysis calculation program, results for the net present value, internal rate of return and the levelized cost of electricity were obtained.

Starting with the net present value, which is shown in Figure 30, it can be noticed that most values are negative. Furthermore, the values follow the same tendency as the electricity production described above. For higher CSP incorporation, the results are better, as well as for the locations with higher solar DNI. Tangier and Sale/Rabat/Kenitra have positive results for 20% of CSP integration. Looking at the best negative results for high CSP integration which are in Ouarzazate and Casablanca, they are less than 5 M€, this value is quite small comparing to the initial investment, which is more than 100 M€.

Actually, the fact that most values are negative is not exactly a bad result. Because, as it happened with many renewable projects such as some wind power farms in Europe, the lifetime of the projects are extended due to maintenance and some renovations. This means the lifetime of the project can be actually extended to more than 24 years as was assumed before. This would also depend on the electricity purchase agreement, which can have a defined deadline or not.

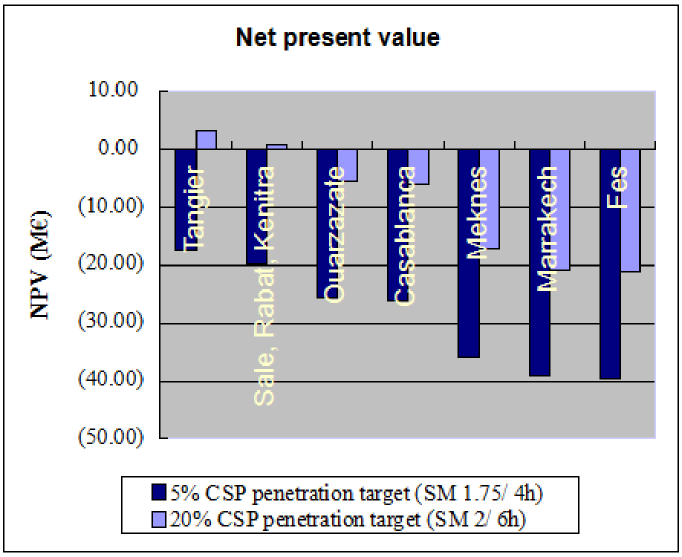


Figure 30 - Economic analysis result for the net present value simulation.

About the internal rate of return, which is shown in Figure 31, it is quite variable. The results are again dominated by the influence of the solar resource, solar multiple (SM) and storage capacity. The worst result with 4.2% is for the location of Fès, for the conditions of lower CSP incorporation target. The best result with 10.2% is for Tangier, with high CSP incorporation target. These huge differences reflect the importance of correct power plant sizing and choosing the best location. Internal rates of return of a project will be analyzed by the investor. The investor is interested in finding high IRR's investments with the lowest risk as possible. The risk is associated not only with the political stability of the country, but also with the proofness of the technology to be used. Within the simulation results, only Tangier, Sale/Rabat/Kenitra, Ouarzazate and Casablanca have good investment conditions for high CSP incorporation target conditions. For only 5% of CSP incorporation conditions, Tangier and Sale/Rabat/Kenitra with 7.55% and 7.22% have the only relatively reasonable results.

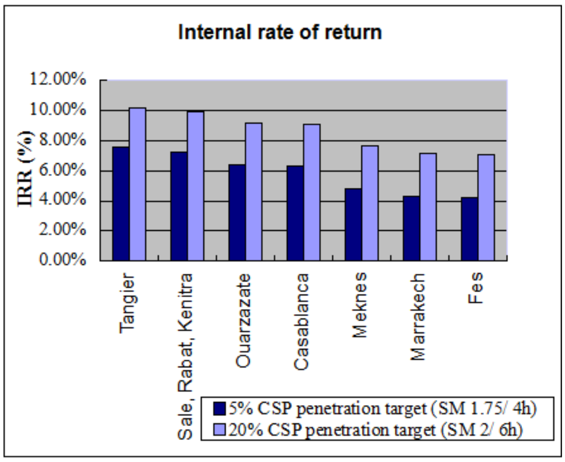


Figure 31 - Economic analysis result for the internal rate of return simulation.

Finally analyzing the Levelized Cost of Electricity, which is presented in Figure 32, the values have the same tendency related to the solar resource, solar multiple and storage capacity conditions as seen above. The LCOE is not dependent on the electricity tariff, which is not a very well fixed value. The best result, for Tangier, Sale/Rabat/Kenitra and high CSP integration, is 12 €cent/kWh. The worst result is 16 €cent/kWh for Fès, Marrakech and Meknes.

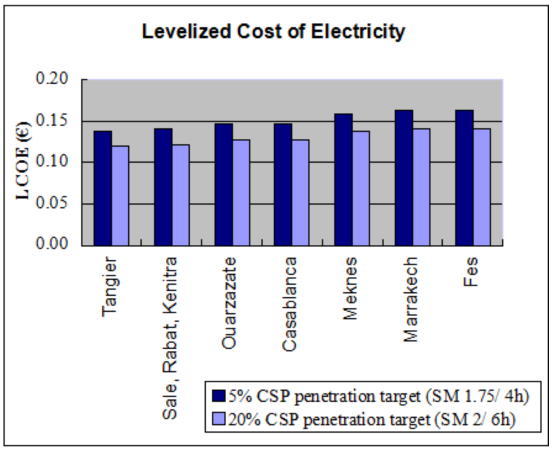


Figure 32 - Economic analysis result for the levelized cost of electricity simulation.

Looking at the Global Status Report (2013) data for LCOE values (Figure 33), values between 12 €cent/kWh and 28 €cent/kWh (using a US$ to € conversion factor of 0.7445) were expected for the simulations. Actually the results were in this interval, which supports that the simulations were carried out with some accurateness. If the used tariff of 0.13 €/kWh (Table 11) would be applied in reality to such a project, it is crucial that the LCOE is at maximum equal to this value, which applies for Tangier, Sale/Rabat/Kenitra, Ouarzazate and Casablanca for 20% of CSP integration.

Technology	**Typical Characteristics**	**Capital Costs** (USD/kW)	**Typical Energy Costs** (LCOE – U.S. cents/kWh)
Power Generation			
Concentrating solar thermal power (CSP)	Types: parabolic trough, Fresnel, tower, dish Plant size: 50–250 MW (trough); 20–250 MW (tower); 10–100 MW (Fresnel) Capacity factor: 20–40% (no storage); 35–75% (with storage)	Trough, no storage: 4,000–7,300 (OECD); 3,100–4,050 (non-OECD) Trough, 6 hours storage: 7,100–9,800 Tower, 6–15 hours storage: 6,300–10,500	Trough and Fresnel: 19–38 (no storage); 17–37 (6 h. storage) Tower: 20–29 (6–7 hours storage); 12–15 (12–15 hours storage)
Solar thermal: Industrial process heat	Collector type: flat-plate, evacuated tube, parabolic trough, linear Fresnel Plant size: 100 kW_{th}–20 MW_{th} Temperature range: 50–400° C	470–1,000 (without storage)	4–16

Figure 33 - LCOE from the Global Status Report 2013 [1H].

3.5 Sensitivity analysis

In order to analyze the results presented above, a sensitivity analysis was carried out for the total construction investment, the electricity tariff and the residual value.

The investment is the sum of all EPC and component costs, not including the yearly operation and maintenance costs. As described before, the investment values used do not include heat exchangers and salt pumps ([3H]). Additionally, the article used as a reference for these values did not specify exactly the sources of their values, and some assumptions were made (such as that the collector cost is equal to the mirrored stainless steel with the same area, excluding the structure. This reference was used because it is relatively recent (2013) and it is very difficult to find real prices for the components from the suppliers (companies do not publish these values nor reply to any contact). This means that the real investment is actually higher than expected in the simulations. On the other hand, as this is a quite recent technology, it is expected that along with the maturation process, component prices are constantly changing and falling down. Therefore, it means that the investment cannot be seen as constant in time nor location, as it changes rapidly depending on when and with who the component/service purchase agreements are made. This sensitivity analysis presents the results for the same conditions as seen in the simulation (chapter Results), except the investment, which deviates ±30% from the reference value used before. The results are only calculated for the best and worst result, which are respectively the location of Tangier and high CSP penetration conditions, and the location of Fès for low CSP integration conditions. The three graphs with the LCOE, NPV and IRR are shown in Figure 34. As it is very obvious, the two result sets - one for the best and one for the worst location - are never brought together, there is still the systematic difference between them. Starting with the LCOE, for both simulations it changes less than 5€cents for more 30% of investment which is actually an important deviation. And, of course, higher investments are bad for the levelized cost of electricity, which rises. The difference is better shown with the NPV value, which changes nearly 40 M€, which is nearly half of the initial investment. Initial investments which are greater than 5% of the reference value, only create negative NPV's. Talking about the IRR, for the best result the minimum value achieved is 7%, which is still an attractive offer for an investor. But for Fès, an attractive result of 8% would only be reached if the initial investment would decrease 30%, which for now is not very realistic.

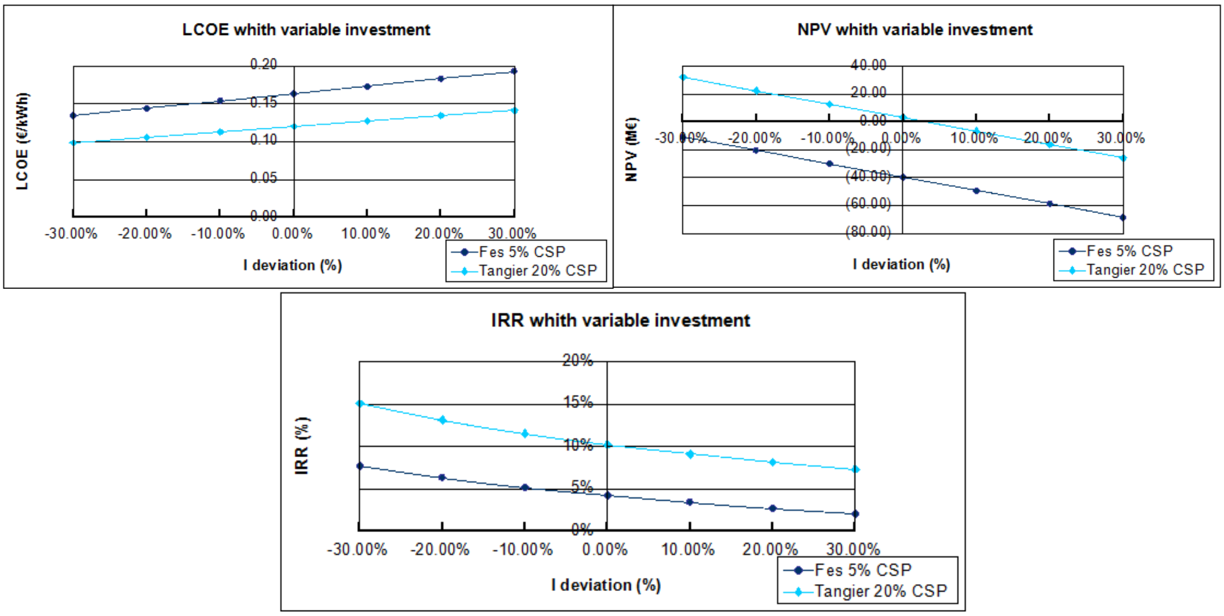


Figure 34 - Variation of LCOE, NPV and IRR for different investment deviations.

The obtained results for different electricity tariffs are shown in the two graphs in Figure 35. First of all, it is clear that the LCOE does not need to be analyzed in this case, since it does not depend on this variable. For the LCOE, the crucial values to be fixed are costs and electricity generation, but the tariff is not involved in the definition of LCOE.

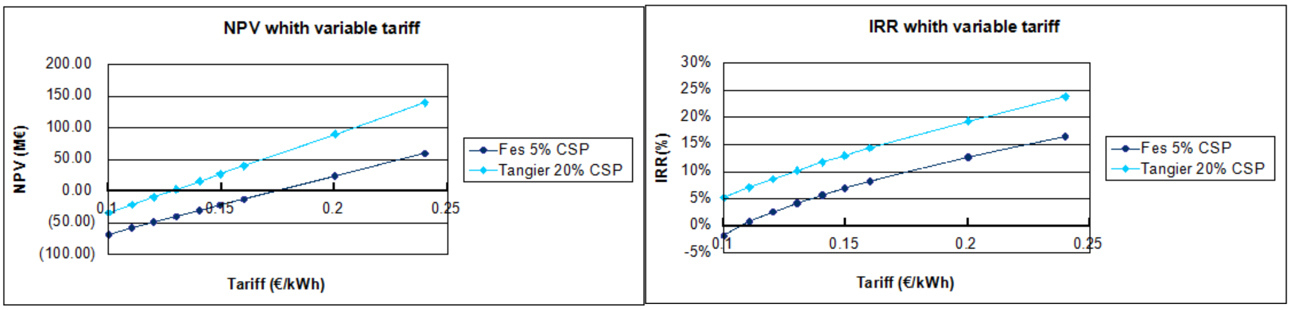


Figure 35 - Variation of NPV and IRR for different electricity tariffs.

For this analysis, the electricity tariff was varied between 10 and 24 €cent/kWh. Again the best and worst results are related to the same conditions as before. For Fès and low CSP integration, the NPV starts to be positive at a tariff of 0.18 €/kWh but the IRR starts to be interesting above 0.15 €/kWh. For Tangier and high CSP integration, the NPV starts to be positive at 0.13 €/kWh, which is exactly the value used in the simulations before. For this situation, any tariff larger than 0.11 €/kWh is Interesting for the investor.

About the sensitivity analysis of the residual value, even a variation of 400% only increased the IRR about 1%. Because of the long lifetime of the project, even large earnings at the end of the lifetime does not have a great impact in the results.

4. Conclusions

The comparison of the dish technology and the parabolic trough technology, including available products in the market, show that the last one is clearly in a more mature state.

The solar dish has a great advantage of being flexible regarding to the energy use (electricity, heat for hot domestic water, for desalination or absorption chillers) and conversion technology (the Stirling engine, Brayton cycle or thermoelectric generators). But it is not being produced for large-scale power plants. There are no benchmark products available, therefore it would not be realistic to estimate the LCOE for a real large scale project as there are not enough real data and too many assumptions can distort the results. Some studies estimate the LCOE, as the two presented at Figure 4. But nor the SES model is now commercially available, nor the approximations for mass production prices apply for the current state of the technology. The only currently available product is the 3 kW Trinum dish from INNOVA. But since there is no mass production even for this product, the price is still too high. For a successful future, new improved systems are needed to attract new investments. There is still a long path to follow, first to overcome the technical challenges, then to address the cost factor and finally to start mass production. Promising projects and developments are currently done by Qnergy, the OMSoP project, BioStirling4SKA, AirlightEnergy and Helios Power. The main reason why there is still no mass production is probably related to the fact that this technology does not include large scale thermal storage systems as the other CSP technologies have. These systems are therefore in terms of services for the national grid comparable to PV systems, which are in an advanced mature state and very competitive in terms of prices. Technical challenges sum up, the tracking system has to be very precise and resistant, for the Stilring engine the working fluid has to be in a closed space to avoid leaks, which is still a great challenge since it operates at very high temperatures and pressure ranges.

On the other hand, the parabolic trough systems are much more developed and have proved reliability in large scale operation for almost 30 years. Comparing to PV, they have the great advantage of relatively low cost thermal storage systems integration. For a grid which in the future aims to operate with predominantly variable energy sources such as solar and wind power, a storage system is crucial especially if hydro storage and thermal backup systems are not enough to keep the electricity grid stable. Another advantage is that the power block is similar to conventional power plants, for which long term experience is available. Hybridization is seen as a great chance to reduce system total costs and at the same time reduce the greenhouse gas emissions.

Incentives from the Spanish and USA governments provided support to the development of parabolic trough plants. This lead to the development of engineering skills in large companies, as well as the development of new collectors and other components. Companies such as Abener/Teyma, Acciona Solar Power, Cobra, Sener and Abantia offer EPC services. Some of them also develop and produce specific components such as the Astrø, the SenerTrough and the ET150 collectors. For the receiver, PTR®70 from Schott is the most used benchmark product.

The economic simulations for Morocco which were carried out relate to the result of the market analysis. Two reference power plants were designed for 5% and 20% of CSP penetration and therefore benchmark components were used.

The cities which have the best solar resource show more attractive results. And, the best results are related to 6h of storage capacity and a solar multiple of 2, which is the most cost effective option for the total electricity grid if CSP would represent 20% of the total installed capacity. This means that if the government would opt for more CSP integration, the most cost effective solution for the grid would be also the most cost effective solution for the project itself.

If the project would be implemented with an electricity tariff of 0.13 €/kWh, the only locations with an LCOE lower than 0.13 €/kWh are Tangier, Sale, Rabat and Kenitra. The correspondent internal rates of return are 10.2% for Tangier and 9.9% for the area of Sale, Rabat and Kenitra, and the net present values are 3.7 M€ (Tangier) and 0.7 M€ (Sale, Rabat and Kenitra). But, as the investment is still a crucial value to be determined in project analysis, it has to be taken into account that a deviation of 30% in the investment can lead to up to 5% of difference in the IRR. For lower investment there will be new locations where it would be economically feasible to install the power plant, and the other way round. The same happens to the tariff, which has a great impact in the results. Variations of 23% lead to changes in the IRR value in the range of 6%. Another aspect which has to be taken into account are the solar resource databases. Different meteorological models lead to different results, which has a great impact while choosing the best location. The meteorological data used by SAM, such as the ambient temperature, wind speed and humidity, which have an impact due to different working conditions for the power plant must also be considered. For example the locations of Ouarzazate, Meknes and Casablanca have only available data for the last three or four years, which is not enough.

More than just analyzing the project, it is important to consider other effects on the electricity grid and local economies. Morocco is highly dependent on foreign energy sources. With growing energy demand and fossil fuel prices, a decision to not use the renewable energy sources available in the country would be a waste of money. And in fact the government decided to pursue with the Solar Program, which aims to start a new era of electricity production.

In the future, the CSP costs are expected to decrease with higher automation at the production lines, more experience, improved materials and large scale production. But the competitiveness comparing to other technologies will depend on the development of those (such as the PV prices and other storage systems such as electro-chemical batteries).

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